DEPENDENCE OF FUEL PROPERTIES DURING BLENDING OF ISO-PARAFFINIC KEROSENE AND PETROLEUM-DERIVED JET FUEL

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14. ABSTRACT
The studies and analysis performed in this report were made to improve the understanding of blending an *Iso*-Paraffinic Kerosene (IPK) produced from natural gas via Fischer-Tropsch (FT) synthesis with several petroleum-derived fuels on the resulting chemical, physical and Fit-For-Purpose (FFP) properties. The IPK had a similar distillation range to a typical jet fuel and high *iso*-/normal alkane ratio. Blending showed a linear dependence in the specification and non-specification properties with blend ratio. Determination and understanding of this dependence allows for the prediction of anticipated fuel properties during blending and for statistical analysis using historical fuel property distribution data to be performed to investigate expected fuel properties and variability as a function of blend ratio.

15. SUBJECT TERMS
Fischer-Tropsch (FT) Fuel, Iso-Paraffinic Kerosene (IPK), blending, chemical and physical fuel properties, Synthetic Paraffinic Kerosene (SPK)

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Table of Contents

List of Figures

List of Tables

1. Executive Summary

There has been increasing interest in recent years in the development and use of aviation fuels derived from non-petroleum feedstocks. The motivation for use of domestically-produced alternative fuels is driven by many factors, including homeland defense, military preparedness and economic security. Development of processes and infrastructure to produce liquid fuels from domestic sources, such as coal or biological feedstocks, could significantly assist in achieving this goal. One approach that can be implemented is the use of Fischer-Tropsch (FT) synthesis to produce liquid fuels via indirect liquefaction. The primary products from low temperature FT synthesis are typically long-chain *n*-alkanes, which can be converted to branched alkanes and separated into the desired distillation range. This product is typically referred to as *Iso*-Paraffinic Kerosene (IPK) and has been produced at large-scale. Several studies have been performed to characterize the use of FT-derived aviation fuels, including qualification of the B-52 and C-17 for use with blends up to 50% by volume of FT-derived IPK with petroleum-derived JP-8. These efforts resulted in the recently modified JP-8 fuel specification (MIL-DTL-83133F) which specified requirements for blending of FT-derived IPK. However, improved understanding on the effect of blending an FT-derived IPK with JP-8 on the resulting chemical, physical and Fit-For-Purpose (FFP) properties is needed. This critical information will provide a basis for subsequent property prediction, potential blend strategies and evaluation of subsequent research fuels.

In this effort, blends of an FT-derived IPK produced from natural gas by Syntroleum Corporation with representative JP-8 fuels from Tinker AFB, Edwards AFB, and several petroleum-derived fuels in the inventory of the Fuels Branch of the Air Force Research Laboratory AFRL/RZPF) at Wright Patterson AFB were prepared. The fuel blend properties were compared to the current JP-8 specification and non-routine analytical testing, including characterization of low temperature behavior and oxidative thermal stability characteristics, was also performed. The resulting blend properties were found to be linearly dependent on the percentage of each fuel blended. This linear dependence was primarily attributed to the specific IPK used in this study which had a similar distillation range to a typical jet fuel with a high *iso*-/normal alkane ratio. This linearity is important for prediction of the maximum blend ratio that can be used while still meeting the current JP-8 specification requirements. Understanding of the property dependence with blending will allow for statistical analysis using historical fuel property distribution data to be performed to investigate expected fuel properties and variability as a function of blend ratio. Further investigation of non-specification and "Fit-for-Purpose" properties is required to assist in ultimate implementation and determine any limitations which exist. This is especially of concern in the event that fuels with significantly different chemical and physical properties are to be evaluated.

2. Introduction

The need to secure sources and reliable feedstocks for the domestic production of liquid hydrocarbon fuels has been a growing concern for the United States (U.S.). The U.S. is heavily dependent on foreign sources for crude oil, many of which are located in unstable regions of the world. Combined with competition by developing nations, these factors could have significant logistical and economic implications. In particular, the Department of Defense (DoD) is concerned how this situation could affect the ability of the military to respond to worldwide situations. Development of a process and infrastructure to produce liquid fuels using domestic feedstocks could help alleviate the current situation and provide future security. Specifically, the production of jet fuels for aviation applications is of interest due to the relatively large quantities required by DoD.

The U.S. has vast resources of solid and non-conventional hydrocarbon reserves. It is believed there are approximately 800 billion barrels of oil equivalent in its coal reserves and approximately 1 trillion barrels of unconventional oil in oil shale. These domestic sources make up more than three times the known Middle East reserves. Coal is of specific interest since an infrastructure already exists for mining, handling and transportation of this feedstock. In addition, biological feedstocks such as algae, grasses and organic wastes are of interest due to the potential reduction in associated carbon footprint when using these feedstocks. It is possible to produce liquid hydrocarbon fuels from non-crude sources via the Fischer-Tropsch (FT) process. FT technology has existed for decades and has been used to produce fuels ranging from gasoline to diesel from sources such as natural gas, coal and biomass. However, several key operating parameters require further development and evaluation prior to successful implementation on larger scales for jet fuel production. These parameters include: maximizing the yield and selectivity to the desired jet fuel product, optimizing the process for the feedstock of choice, and minimizing undesired emissions and by-products during production. Most importantly, the jet fuel produced via the FT process must be compatible for use with legacy aircraft as well as next-generation platforms. Therefore, evaluation of the fuel product for use in these applications is of significant importance. The DoD, in conjunction with the Department of Energy and Industry, has been working to develop, test, certify and use jet fuels produced via FT synthesis.[1-7]

The primary products from low temperature (210-240°C) FT synthesis are typically long chain n-alkanes (wax). It is possible to use the n-alkanes directly as a diesel fuel following separation; this high cetane fuel can readily be used in existing compression ignition engines. However, the direct FT paraffinic product is not viable for aviation applications due to related undesirable low temperature properties and density issues. The n-alkanes can be hydro-isomerized and hydrocracked to branched alkanes, primarily mono- and di-methyl substituted, and separated into the desired distillation range. This product is typically referred to as *Iso-Paraffinic Kerosene* (IPK) and has been produced at large-scale.[7] An alternative approach is to synthesize IPK using C_3 and C_4 olefins produced in the FT synthesis, as employed by SASOL.[8-9] The C_3 and C_4 olefins are oligomerized followed by hydrotreating and distillation to produce an IPK with the required volatility range for aviation fuel. Several studies have been performed to characterize the use of upgraded FT-derived fuels for aviation applications.[1-2,8-19] Studies with neat FT fuels have demonstrated that significant improvements in thermal oxidative stability and emission production can be realized while superior low-temperature properties can be achieved

with a sufficiently high *iso*-alkane/*n*-alkane ratio. However, the IPK will not meet the JP-8 specification density requirement (minimum 0.775 g/mL) or potentially other specification and "Fit-for-Purpose" (FFP) properties. The FFP properties refer to fuel characteristics which are needed for safe operation but are not directly evaluated via a specification test.

It may be necessary to blend an FT-derived IPK with petroleum-derived fuel for ultimate implementation. This is due both to the inability of IPK to directly satisfy required specification and FFP properties and to anticipated near-term production limitations. Blending of the IPK with a petroleum-derived or alternate synthetic feed has shown that fuel specification requirements can be met, albeit with reduced operational improvements relative to the neat IPK. The United Kingdom Ministry of Defence DEF STAN 91-91 Turbine Fuel Standard allows for the use of a blend up to 50% IPK in a petroleum-derived Jet A-1 provided that the mixture has a minimum 8% aromatic content and satisfies all specification requirements. This fuel, produced by SASOL and termed Semi-Synthetic Jet Fuel, has been reported to have overall properties and functionality consistent with a typical Jet A-1.[8] SASOL has also developed a "Fully Synthetic Jet Fuel" by blending IPK with various hydrocarbon process streams; these mixtures have been shown to conform to all required Jet A-1 properties.[9] The JP-8 Military Fuel Specification, MIL-DTL-83133F, was recently modified (11 April 2008) to allow for blending up to 50% IPK (termed Synthetic Paraffinic Kerosene (SPK)) with a certification JP-8. Similar to the DEF STAN 91-91, the resulting mixture must also have a minimum 8% aromatic content and satisfy all other specification requirements. The standard also specifies the allowable temperature range for 10%, 20% and 90% distillation recovery limits and minimum differentials for the 50% and 90% recovery temperatures from that for the 10%. These requirements ensure that the blending process does not significantly alter the volatility range from that for a typical fuel.

The current specifications for use of IPK were developed using the best available knowledge and guidance. However, improved understanding of the effect of blending on the resulting fuel properties will assist to identify any possible implementation limitations, predict the expected fuel properties and behavior, and determine if it is feasible to use higher blend concentrations than currently permitted. Limited studies have been performed for this purpose, but these have focused on low blend percentages (< 25-50%) of FT and not the dependence of the fuel properties with blending.[8] Higher blend concentrations (of FT) need to be considered since these may be pertinent depending on factors such as the location of the FT production and blending opportunity. In addition, it is desirable to still realize operational benefits while using FT fuels, which are related to the overall IPK content.

Paraffinic fuels produced via the Shell Middle Distillate Synthesis (SMDS) have previously been characterized both neat and as a blend with various petroleum-derived fuels.[10] The SMDS fuels were narrow cut fuels (Distillation 160-200°C) as compared to typical aviation fuel (205-300°C), consisting of normal and branched paraffins with carbon numbers from C_8-C_{13}. The fuels had relatively high *n*-alkane/*iso*-alkane ratios of 1.8 and 2.7. Several specification, non-specification and FFP properties were evaluated, primarily at low blend concentrations ($< 25\%$). For higher blend concentrations, only limited testing related to specific performance requirements were performed. Overall, these studies generally demonstrated that the fuel properties varied linearly with blend ratio, with the exception of the fuel freeze point. A separate detailed analysis and study was performed to evaluate potential implications of blending

an FT fuel with petroleum-derived JP-8 feedstocks on the resulting physical properties.[20] The detailed analysis was performed to predict "virtual blend" properties using the Defense Energy Support Center "Petroleum Quality Information System" (PQIS) database for JP-8 fuel procured during 2004 and assumed a linear dependence on blend ratio. This analysis primarily focused on the anticipated density and aromatic content and whether these would satisfy the DEF STAN 91-91 requirements. Blends of up to 50% FT with "typical" JP-8 fuels, which ranged from ~14-20% in aromatic content, were also prepared for limited specification testing. These studies reported a linear dependence of density for the range studied.

Based on the many factors discussed and limited available data, evaluation of the effect of blending an FT-derived IPK with JP-8 fuel on the resulting chemical, physical and FFP properties is warranted. This critical information would provide a basis for subsequent property prediction, potential blend strategies and evaluation of subsequent research fuels. The use of a representative IPK can provide an initial basis for evaluation, rather than using an FT fuel that has already been supplemented with other components, such as aromatics. The IPK should have a molecular weight distribution (e.g., distillation range) consistent with a typical jet fuel to alleviate potential issues related to varying volatility (flash point) and also have a high *iso-/n*-alkane ratio. The evaluation should be performed over the full range of blend mixtures (0-100%) with a very wide range of petroleum-derived fuels to investigate if the functional dependence varies with feedstock specific properties.

3. Summary of Analytical Results for FT Blends

A Fischer-Tropsch fuel produced from natural gas by Syntroleum Corporation was blended with a total of eight JP-8 and Jet A (with JP-8 additives) fuels for evaluation of the dependence of the resulting fuel properties on blending. The FT fuel was completely paraffinic, with an *iso-/n*-alkane ratio of approximately 4.8 (82% *iso*-alkane) and a distillation range similar to that of a typical aviation fuel. Although this fuel is not solely comprised of *iso*-alkanes, it will be referred to as IPK due to the relatively high ratio. The chromatograms of the Syntroleum fuel and a typical JP-8 obtained using Gas Chromatography/Mass Spectrometry (GC-MS) are shown in Figure 1. The IPK was treated with the JP-8 fuel additives at required dosages. This fuel was used for the qualification of the B-52 for operation with a 50% blend of IPK.[4,7,17] The petroleum-derived fuels included JP-8 fuels acquired from the active fuel inventories at Tinker AFB and Edwards AFB, and several other fuels from research facilities. These fuels comprised a wide range of physical and chemical properties consistent with those typically observed for JP-8. The FT fuel was blended into each petroleum fuel at a volume percentage of 0, 25, 37.5, 50, and 75%. All blends and neat fuels were subjected to specification and non-specification testing to examine the dependence of blending on the resulting properties.

This document provides a summary of the analytical results obtained for the various blends of the petroleum-derived fuels with the FT fuel. Section 3.1 describes the fuels and fuel blends analyzed for this effort. Section 3.2 provides a summary of the specification test reports generated by the Air Force Petroleum Agency (AFPA/AFTT) at Wright Patterson AFB with related discussion of the dependence of properties with blending. Section 3.3 describes the non-routine analytical tests conducted by The Fuels Branch of the Air Force Research Laboratory (AFRL/RZPF) and the University of Dayton Research Institute (UDRI); these non-routine tests include hydrocarbon type analysis, *n*-alkane analysis, polars analysis, surface tension measurements, sulfur speciation, and low temperature viscosity. This section also includes additional discussion of the heat of combustion measurements. Section 3.4 provides a summary of the thermal stability results as measured by the Quartz Crystal Microbalance (QCM). Section 3.5 describes laboratory storage stability via low pressure reactor measurements. Section 3.6 is a compilation of GC-MS chromatograms for each of the neat petroleum fuels, the FT fuel and a 50% volume blend. An appendix contains dynamic viscosity curves.
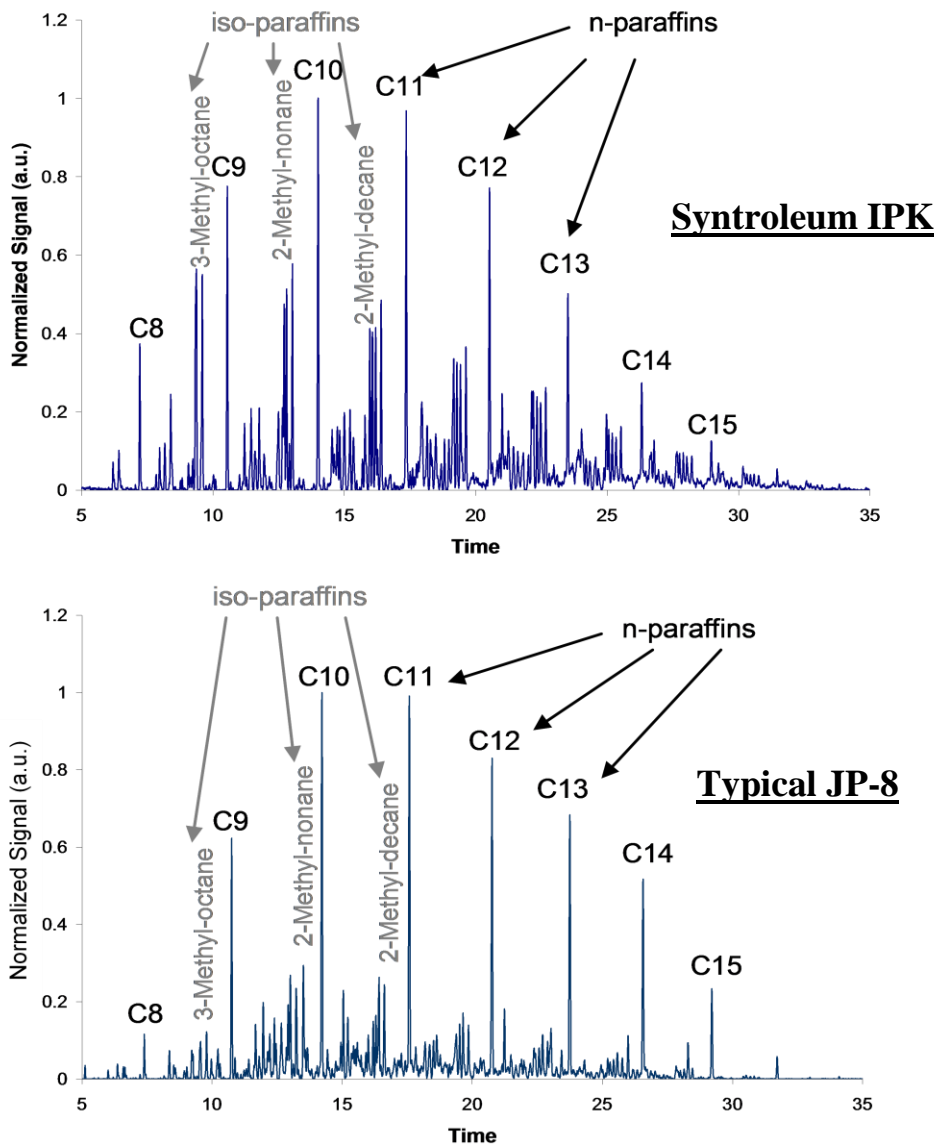
Figure 1. Chromatograms of the Syntroleum Fischer-Tropsch IPK and a typical JP-8.

3.1. Fuels and Fuel Blends Analysis

The list of the fuels and blends examined during the blending study is provided in Table 1. The fuels from Tinker and Edwards AFBs were used as representative fuels obtainable at those locations to investigate the anticipated properties for blends prepared during the B-52 engine and flight tests. The AFRL/RZPF fuels were selected to span a wide range of potential feedstocks typical of those available in the Continental United States (CONUS). These included both specification JP-8s and Jet A fuels with the required JP-8 additives. A blend of 75% FT with 25% F3694 was not prepared due to the limited available quantity of the latter.

Table 1. List of fuels and blends evaluated for specification and non-specification properties. The fuel F4909 is the Fischer-Tropsch IPK with JP-8 additives.

Fuel ID	Fuel Description	Fuel ID	Fuel Description
F4909	Fischer-Tropsch (FT) IPK F4909		
F4911	JP-8 from Edwards AFB	F3804	JP-8
F4924	25% F4909/ 75% F4911	F4914	25% F4909/ 75% F3804
F4933	37.5% F4909/ 62.5% F4911	F4935	37.5% F4909/ 62.5% F3804
F4925	50% F4909/ 50% F4911	F4915	50% F4909/ 50% F3804
F4932	75% F4909/ 25% F4911	F4934	75% F4909/ 25% F3804
F4908	JP-8 from Tinker AFB	F3694	Jet A with JP-8 additives
F4922	25% F4909/ 75% F4908	F4920	25% F4909/ 75% F3694
F4931	37.5% F4909/ 62.5% F4908	F4942	37.5% F4909/ 62.5% F3694
F4923	50% F4909/ 50% F4908	F4921	50% F4909/ 50% F3694
F4930	75% F4909/ 25% F4908		
F4751	JP-8	F3602	Jet A with JP-8 additives
F4912	25% F4909/ 75% F4751	F4916	25% F4909/ 75% F3602
F4929	37.5% F4909/ 62.5% F4751	F4939	37.5% F4909/ 62.5% F3602
F4913	50% F4909/ 50% F4751	F4917	50% F4909/ 50% F3602
F4928	75% F4909/ 25% F4751	F4938	75% F4909/ 25% F3602
F4177	JP-8	F3166	Jet A with JP-8 additives
F4926	25% F4909/ 75% F4177	F4918	25% F4909/ 75% F3166
F4937	37.5% F4909/ 62.5% F4177	F4941	37.5% F4909/ 62.5% F3166
F4927	50% F4909/ 50% F4177	F4919	50% F4909/ 50% F3166
F4936	75% F4909/ 25% F4177	F4940	75% F4909/ 25% F3166

3.2. Specification Test Results

The results of the specification tests performed on the varying blend concentrations of the IPK with the various petroleum-derived fuels are summarized in Tables 2-9. Generally, the FT fuel changed the properties of the petroleum fuel linearly during blending, as would be expected by dilution theory. For example, the FT fuel decreased aromatic content in direct proportion to the amount of the dilution of the petroleum fuel. To demonstrate the effect of dilution on specification properties and provide discussion on potential implications of the change in property values, plots were prepared for select properties as a function of blend percentage of FT (see Figures 2-11). Only two of the eight petroleum fuels were chosen for each plot for discussion; the fuels shown exhibited the maximum and minimum values for each respective specification property. The behavior observed for the selected fuels was consistent to that for all other fuels evaluated.

Overall, the linear dependence of the specification fuel properties with blend percentage is important and useful for determination of the maximum allowable blend ratio of the IPK. The two properties that should be of greatest interest are the aromatic content and density. The aromatic content is important since it is believed to relate to seal-swell and compatibility of various materials; improvement in the understanding of this phenomena and influence of aromatic type and functionality is needed. For all properties investigated, only one failure was observed for blends of 50% FT (with the standard JP-8 military additive package) and 50% petroleum-derived fuels (aromatic content for blend with POSF 4908). This was attributed to the neat JP-8 fuel having an aromatic content below 16.0%. In some cases, the electrical conductivity and FSII content may be under the specification level; however, these properties are controlled and easily adjusted by the corresponding additive content.

Table 2. Specification test results for blends with JP-8 fuel F4911 from Edwards AFB.

		spec min	spec max	4909(100%) FT Liquid	4909 (75%) 4911 (25%) 4932	4909 (50%) 4911 (50%) 4925	4909 (37.5%) 4911 (62.5%) 4933	4909 (25%) 4911 (75%) 4924	4909(0%) 4911(100%) 4911
SPEC/W	Workmanship		pass	pass	pass	pass	pass	pass	pass
D3242	Total Acid Num. (mg KOH/g)		0.10	0.004	0.004	0.005	0.004	0.003	0.004
D1319	Aromatics, vol %		25.0	0	3.2	8.3	9.5	12.1	16.5
D6379	Aromatics, vol % by HPLC		Report	<0.2	4.1	8.1	10.1	12.1	16.3
D3227	Mercaptan Sulfur, wt %		0.002	0.000	0.000	0.000	0.000	0.000	0.000
D4294	Total Sulfur, wt%		0.30	0.002	0.0167	0.029	0.039	0.044	0.060
	Distillation D86 or D2887								
	IBP, deg C		Report	144	146	148	152	151	145
	10% recovered, deg C		205	167	167	170	171	171	172
	20% recovered, deg C		Report	177	177	179	179	180	181
	50% recovered, deg C		Report	206	205	206	204	205	205
	90% recovered, deg C		Report	256	252	253	249	251	252
	EF, deg C		300	275	276	275	276	277	277
	Residue, vol%		1.5	1.5	1.0	1.3	0.7	1.4	1.3
	loss, vol%		1.5	0.9	0.0	1.1	0.0	0.3	1.3
D93	Flash point, degrees C	38		45	45	48	46	46	48
D5972	Freeze Point, degrees C		-47	-51	-51	-52	-51	-51	-52
D445	Viscosity @ -20, cSt		8.0	4.9	4.5	4.6	4.5	4.6	4.8
D445	Viscosity @ -40, cSt		Report	9.5	9.3	9.3	9.2	9.4	9.4
D4809	Heat of Comb.(meas),BTU/lb	Report		18870	18780	18680	18620	18520	18520
D3338	Heat of Comb. (calc), BTU/lb	18400		18980	18850	18680	18730	18680	18590
D5865	net Heat Comb. (meas), BTU/lb	Report		18703	18180	17800	18480	18130	18240
D3343	Hydrogen Content, wt %	13.4		15.4	15.0	14.5	14.4	14.2	13.8
D1322	Smoke Point, mm	19.0		42.0	40.0	34.0	28.0	29.0	23.0
D1840	Naphthalenes, vol %		3.0	NR	NR	NR	NR	NR	1.2
D130	Copper Strip Corrosion		1	1a	1a	1a	1a	1a	1a
D3241	Thermal Stability @ 260°C								
	Tube Deposit Rating		<3	1	1	1	1	1	0
	Change in Pressure, mmHg		25	0	1	5	7	1	0
D381	Existent Gum, mg/100mL		7.0	0.6	1.2	0.4	0.6	1.8	0.8
D5452	Particulate Matter, mg/L		1.0	1.0					0.3
	Filtration Time, minutes		15	10					4
D1094	Water Reaction		1B	1	1	1	1	1	1
D5006	FSII, vol%	0.10	0.15	0.10	0.11	0.10	0.12	0.11	0.11
D2624	Conductivity, pS/m	150	600	456	232	305	192	204	177
D4052	API Gravity @ 60 F	37.0	51.0	55.6	52.4	49.4	48.0	46.6	43.8
D4052	specific gravity, g/mL	0.840	0.775	0.756	0.769	0.782	0.788	0.794	0.807
D5001	Lubricity (BOCLE), mm		Report	0.58	0.50	0.54	0.52	0.53	0.56
D5185	copper ICP, ug/L		Report	8	<5	8	<5	<5	8
D5185	zinc ICP, ug/L		Report	232	63	266	<50	122	193
D1331	surface tension, dynes/cm		Report	23.7		24.5		24.9	25.5

note - yellow highlight indicates out of spec range

Table 3. Specification test results for blends with JP-8 fuel F4908 from Tinker AFB.

SPEC/W		spec min	spec max	4909(100%) FT Liquid	4909 (75%) 4908 (25%) 4930	4909 (50%) 4908 (50%) 4923	4909 (37.5%) 4908 (62.5%) 4931	4909 (25%) 4908 (75%) 4922	4909(0%) 4908(100%) 4908
SPEC/W	Workmanship		pass	pass	pass	pass	pass	pass	pass
D3242	Total Acid Num. (mg KOH/g)		0.10	0.004	0.004	0.003	0.006	0.003	0.003
D1319	Aromatics, vol %		25.0	0	2.4	6.1	7.6	9.5	13.6
D6379	Aromatics, vol % by HPLC		Report	<0.2	3.4	6.5	8.1	9.6	12.9
D3227	Mercaptan Sulfur, wt %		0.002	0.000	0.000	0.000	0.000	0.000	0.001
D4294	Total Sulfur, wt%		0.30	0.002	0.019	0.034	0.045	0.050	0.070
	Distillation D86 or D2887								
	IBP, deg C		Report	144	152	154	164	168	178
	10% recovered, deg C		205	167	172	179	183	187	193
	20% recovered, deg C		Report	177	182	189	190	194	197
	50% recovered, deg C		Report	206	207	209	209	209	209
	90% recovered, deg C		Report	256	249	246	241	240	235
	EF, deg C		300	275	273	269	265	263	255
	Residue, vol%		1.5	1.5	1.0	1.4	1.0	1.2	1.2
	loss, vol%		1.5	0.9	0.1	0.8	0.1	0.1	0.2
D93	Flash point, degrees C	38		45	47	52	54	57	64
D5972	Freeze Point, degrees C		-47	-51	-52	-54	-53	-52	-51
D445	Viscosity @ -20, cSt		8.0	4.9	4.9	4.9	4.9	5.1	5.1
D445	Viscosity @ -40, cSt		Report	9.5	9.8	10.8	10.4	10.5	11.1
D4809	Heat of Comb.(meas),BTU/lb	Report		18870	18790	18260	18570	18580	18570
D3338	Heat of Comb. (calc), BTU/lb	18400		18980	18900	18790	18750	18700	18620
D5865	net Heat Comb. (meas), BTU/lb	Report		18700	18450	18610	18550	18400	18520
D3343	Hydrogen Content, wt %	13.4		15.4	15.1	14.6	14.5	14.3	13.9
D1322	Smoke Point, mm	19.0		42.0	41.0	34.0	34.0	29.0	25.0
D1840	Naphthalenes, vol %		3.0	NR	NR	NR	NR	NR	1.4
D130	Copper Strip Corrosion		1	1a	1a	1a	1a	1a	1a
D3241	Thermal Stability @ 260°C								
	Tube Deposit Rating		<3	1	2	1	1	1	0
	Change in Pressure, mmHg		25	0	4	2	2	1	0
D381	Existent Gum, mg/100mL		7.0	0.6	0.8	0	1.4	0.4	0.8
D5452	Particulate Matter, mg/L		1.0	1.0					4.3
	Filtration Time, minutes		15	10					5
D1094	Water Reaction		1B	1	1	1b	1	1	1
D5006	FSII, vol%	0.10	0.15	0.10	0.10	0.10	0.11	0.11	0.10
D2624	Conductivity, pS/m	150	600	456	303	282	218	221	184
D4052	API Gravity @ 60 F	37.0	51.0	55.6	53	49.4	48.0	46.6	43.7
D4052	specific gravity, g/mL	0.840	0.775	0.756	0.767	0.782	0.788	0.794	0.808
D5001	Lubricity (BOCLE), mm		Report	0.58	0.52	0.53	0.53	0.53	0.56
D5185	copper ICP, ug/L		Report	8	<5	<5	<5	<5	<5
D5185	zinc ICP, ug/L		Report	232	66	167	<50	94	65
D1331	surface tension, dynes/cm		Report	23.7		24.7		24.9	25.6

note - yellow highlight indicates out of spec range

Table 4. Specification test results for blends with JP-8 fuel F4751.

		spec min	spec max	4909(100%) FT Liquid 4909	4909(75%) 4751(25%) 4928	4909 (50%) 4751 (50%) 4913	4909 (37.5%) 4751 (62.5%) 4929	4909 (25%) 4751 (75%) 4912	4909(0%) 4751(100%) 4751
SPEC/W	Workmanship		pass	pass	pass	pass	pass	pass	Pass
D3242	Total Acid Num. (mg KOH/g)		0.10	0.004	0.003	0.004	0.003	0.002	0.003
D1319	Aromatics, vol %		25.0	0	4.7	9.8	11.8	14.5	18.8
D6379	Aromatics, vol % by HPLC		Report	<0.2	4.9	10	12.3	14.7	19.6
D3227	Mercaptan Sulfur, wt %		0.002	0.000	0.000	0.000	0.000	0.000	0.000
D4294	Total Sulfur, wt%		0.30	0.002	0.010	0.016	0.026	0.025	0.038
	Distillation D86 or D2887								
	IBP, deg C		Report	144	151	155	156	150	159
	10% recovered, deg C		205	167	170	175	175	177	182
	20% recovered, deg C		Report	177	180	183	184	186	189
	50% recovered, deg C		Report	206	207	208	207	208	208
	90% recovered, deg C		Report	256	252	250	247	247	244
	EF, deg C		300	275	274	272	270	268	265
	Residue, vol%		1.5	1.5	1.4	1.1	1.0	1.3	1.3
	loss, vol%		1.5	0.9	0.2	0.8	0.0	0.8	0.8
D93	Flash point, degrees C	38		45	43	47	47	48	51
D5972	Freeze Point, degrees C		-47	-51	-50	-51	-50	-51	-50
D445	Viscosity @ -20, cSt		8.0	4.9	4.6	4.7	4.8	4.7	4.9
D445	Viscosity @ -40, cSt		Report	9.5	9.5	9.7	9.6	10.2	9.9
D4809	Heat of Comb.(meas),BTU/lb	Report		18870	18540	18640	18600	18400	17930
D3338	Heat of Comb. (calc), BTU/lb	18400		18980	18870	18760	18720	18680	18590
D5865	net Heat Comb. (meas), BTU/lb	Report		18700	18550	18480	18570	18290	18340
D3343	Hydrogen Content, wt %	13.4		15.4	14.9	14.5	14.3	14.1	13.8
D1322	Smoke Point, mm	19.0		42.0	40.0	32.0	29.0	28.0	22.0
D1840	Naphthalenes, vol %		3.0	NR	NR	NR	NR	NR	1.2
D130	Copper Strip Corrosion		1	1a	1a	1a	1a	1a	1a
D3241	Thermal Stability @ 260°C								
	Tube Deposit Rating		<3	1	1	1	1	1	1
	Change in Pressure, mmHg		25	0	6	6	0	0	2
D381	Existent Gum, mg/100mL		7.0	0.6	1.8	0	0.8	1.4	0.4
D5452	Particulate Matter, mg/L		1.0	1.0					0.3
	Filtration Time, minutes		15	10					4
D1094	Water Reaction		1B	1	1	1	1	1b	1
D5006	FSII, vol%	0.10	0.15	0.10	0.10	0.10	0.11	0.09	0.07
D2624	Conductivity, pS/m	150	600	456	264	215	103	120	112
D4052	API Gravity @ 60 F	37.0	51.0	55.6	52.6	49.8	48.4	47.1	44.4
D4052	specific gravity, g/mL	0.840	0.775	0.756	0.769	0.780	0.787	0.792	0.804
D5001	Lubricity (BOCLE), mm		Report	0.58	0.53	0.54	0.51	0.59	0.53
D5185	copper ICP, ug/L		Report	8	<5	<5	<5	<5	<5
D5185	zinc ICP, ug/L		Report	232	199	118	52	128	155
D1331	surface tension, dynes/cm		Report	23.7		24.4		24.8	25.5

note - yellow highlight indicates out of spec range

11

Table 5. Specification test results for blends with JP-8 fuel F4177.

		spec min	spec max	4909(100%) FT Liquid 4909	4909 (75%) 4177 (25%) 4936	4909 (50%) 4177 (50%) 4927	4909 (37.5%) 4177 (62.5%) 4937	4909 (25%) 4177 (75%) 4926	4909(0%) 4177(100%) 4177
SPEC/W	Workmanship		pass	pass	pass	pass	pass	pass	pass
D3242	Total Acid Num. (mg KOH/g)		0.10	0.004	0.004	0.003	0.006	0.003	0.004
D1319	Aromatics, vol %		25.0	0	3.4	8.7	9.8	12.7	16.9
D6379	Aromatics, vol % by HPLC		Report	<0.2	4.3	8.2	10.6	12.6	17.3
D3227	Mercaptan Sulfur, wt %		0.002	0.000	0.000	0.000	0.000	0.001	0.001
D4294	Total Sulfur, wt%		0.30	0.002	0.036	0.065	0.092	0.100	0.133
	Distillation D86 or D2887								
	IBP, deg C		Report	144	146	148	151	152	162
	10% recovered, deg C		205	167	170	174	176	178	183
	20% recovered, deg C		Report	177	180	184	186	187	190
	50% recovered, deg C		Report	206	207	207	207	207	207
	90% recovered, deg C		Report	256	250	248	244	243	237
	EF, deg C		300	275	273	272	271	269	265
	Residue, vol%		1.5	1.5	1.4	1.2	1.4	1.4	1.2
	loss, vol%		1.5	0.9	0.1	1.1	0.1	0.9	0.7
D93	Flash point, degrees C	38		45	46	48	49	50	52
D5972	Freeze Point, degrees C		-47	-51	-54	-57	-56	-58	-58
D445	Viscosity @ -20, cSt		8.0	4.9	4.6	4.6	4.7	4.8	4.8
D445	Viscosity @ -40, cSt		Report	9.5	9.3	10.5	10.5	10.0	10.2
D4809	Heat of Comb.(meas),BTU/lb	Report		18870	18750	18630	18600	18510	16680
D3338	Heat of Comb. (calc), BTU/lb	18400		18980	18860	18750	18700	18640	18540
D5865	net Heat Comb. (meas), BTU/lb	Report		18700	17500	18580	18340	17900	18240
D3343	Hydrogen Content, wt %	13.4		15.4	14.9	14.5	14.3	14.1	13.7
D1322	Smoke Point, mm	19.0		42.0	35.0	33.0	26.0	27.0	22.0
D1840	Naphthalenes, vol %		3.0	NR	NR	NR	NR	NR	1.0
D130	Copper Strip Corrosion		1	1a	1a	1a	1a	1a	1a
D3241	Thermal Stability @ 260°C								
	Tube Deposit Rating		<3	1	1	1	1	0	1
	Change in Pressure, mmHg		25	0	1	0	0	0	1
D381	Existent Gum, mg/100mL		7.0	0.6	0	1.4	2	0.4	0.6
D5452	Particulate Matter, mg/L		1.0	1.0					
	Filtration Time, minutes		15	10					
D1094	Water Reaction		1B	1	1	1	1b	1	1
D5006	FSII, vol%	0.10	0.15	0.10	0.10	0.10	0.09	0.10	0.10
D2624	Conductivity, pS/m	150	600	456	280	263	105	121	97
D4052	API Gravity @ 60 F	37.0	51.0	55.6	51.9	48.7	47.1	45.4	42.2
D4052	specific gravity, g/mL	0.775	0.840	0.756	0.772	0.785	0.792	0.800	0.815
D5001	Lubricity (BOCLE), mm		Report	0.58	0.57	0.58	0.59	0.56	0.56
D5185	copper ICP, ug/L		Report	8	<5	6	7	<5	6
D5185	zinc ICP, ug/L		Report	232	79	118	126	<50	146
D1331	surface tension, dynes/cm		Report	23.7		24.7		25.2	25.6

note: yellow highlight indicates out of spec range

12

Table 6. Specification test results for blends with JP-8 fuel F3804.

SPEC/W		spec min	spec max	4909(100%) FT Liquid	4909 (75%) 3804 (25%) 4934	4909 (50%) 3804 (50%) 4915	4909 (37.5%) 3804 (62.5%) 4935	4909 (25%) 3804 (75%) 4914	4909(0%) 3804(100%) 3804
SPEC/W	Workmanship		pass	pass	pass	pass	pass	pass	pass
D3242	Total Acid Num. (mg KOH/g)		0.10	0.004	0.005	0.004	0.004	0.004	0.005
D1319	Aromatics, vol %		25.0	0	4.8	9.7	11.1	15.2	20.3
D6379	Aromatics, vol % by HPLC		Report	<0.2	4.9	9.6	12.5	15.1	20
D3227	Mercaptan Sulfur, wt %		0.002	0.000	0.000	0.000	0.000	0.000	0.000
D4294	Total Sulfur, wt%		0.30	0.002	0.019	0.035	0.048	0.053	0.073
	Distillation D86 or D2887								
	IBP, deg C		Report	144	151	148	147	150	160
	10% recovered, deg C		205	167	169	171	173	174	177
	20% recovered, deg C		Report	177	178	180	181	181	183
	50% recovered, deg C		Report	206	204	203	202	202	200
	90% recovered, deg C		Report	256	250	247	244	242	237
	EF, deg C		300	275	273	268	265	263	255
	Residue, vol%		1.5	1.5	1.2	1.3	1.5	1.2	1.2
	loss, vol%		1.5	0.9	0.4	0.8	0.3	0.9	0.7
D93	Flash point, degrees C	38		45	46	48	46	50	52
D5972	Freeze Point, degrees C		-47	-51	-51	-53	-51	-50	-49
D445	Viscosity @ -20, cSt		8.0	4.9	4.4	4.4	4.2	4.3	4.2
D445	Viscosity @ -40, cSt		Report	9.5	9.2	9.0	8.4	8.7	8.3
D4809	Heat of Comb.(meas),BTU/lb	Report		18870	18720	17740	18600	18550	18470
D3338	Heat of Comb. (calc), BTU/lb	18400		18980	18840	18790	18740	18680	18590
D5865	net Heat Comb. (meas), BTU/lb	Report		18700	18540	18370	18430	17500	18400
D3343	Hydrogen Content, wt %	13.4		15.4	14.8	14.6	14.4	14.2	13.8
D1322	Smoke Point, mm	19.0		42.0	32.0	33.0	31.0	28.0	23.0
D1840	Naphthalenes, vol %		3.0	NR	NR	NR	NR	NR	1.9
D130	Copper Strip Corrosion		1	1a	1a	1a	1a	1a	1a
D3241	Thermal Stability @ 260°C								
	Tube Deposit Rating		<3	1	1	1	<1	1	1
	Change in Pressure, mmHg		25	0	1	2	0	2	1
D381	Existent Gum, mg/100mL		7.0	0.6	0.0	2.0	0.4	1.2	0.2
D5452	Particulate Matter, mg/L		1.0	1.0					
	Filtration Time, minutes		15	10					
D1094	Water Reaction		1B	1	1	1	1	1b	1
D5006	FSII, vol%	0.10	0.15	0.10	0.10	0.09	0.10	0.09	0.09
D2624	Conductivity, pS/m	150	600	456	290	289	147	167	119
D4052	API Gravity @ 60 F	37.0	51.0	55.6	52.9	50.5	49.2	48	45.7
D4052	specific gravity, g/mL	0.840	0.775	0.756	0.767	0.777	0.783	0.788	0.799
D5001	Lubricity (BOCLE), mm		Report	0.58	0.54	0.57	0.57	0.57	0.56
D5185	copper ICP, ug/L		Report	8	<5	8	5	9	10
D5185	zinc ICP, ug/L		Report	232	85	220	60	173	150
D1331	surface tension, dynes/cm		Report	23.7		24.4		24.7	25.3

note - yellow highlight indicates out of spec range

Table 7. Specification test results for blends with Jet A (with JP-8 Additives) F3694.

		spec min	spec max	4909(100%) FT Liquid	4909 (50%) 3694 (50%) 4921	4909 (37.5%) 3694 (62.5%) 4942	4909 (25%) 3694 (75%) 4920	4909(0%) 3694(100%) 3694
SPEC/W	Workmanship		pass	pass	pass	pass	pass	pass
D3242	Total Acid Num. (mg KOH/g)		0.10	0.004	0.006	0.007	0.006	0.009
D1319	Aromatics, vol %		25.0	0	8.4	10.1	12.6	16.6
D6379	Aromatics, vol % by HPLC		Report	<0.2	7.9	-	11.9	15.9
D3227	Mercaptan Sulfur, wt %		0.002	0.000	0.000	0.000	0.001	0.001
D4294	Total Sulfur, wt%		0.30	0.002	0.083	0.115	0.123	0.172
	Distillation D86 or D2887							
	IBP, deg C		Report	144	148	153	155	152
	10% recovered, deg C		205	167	170	172	172	174
	20% recovered, deg C		Report	177	180	180	181	183
	50% recovered, deg C		Report	206	206	204	205	205
	90% recovered, deg C		Report	256	251	246	246	244
	EF, deg C		300	275	272	271	270	266
	Residue, vol%		1.5	1.5	1.4	1.1	1.0	1.1
	loss, vol%		1.5	0.9	1.1	0.0	0.6	1.0
D93	Flash point, degrees C	38		45	52	47	48	51
D5972	Freeze Point, degrees C		-47	-51	-52	-51	-51	-50
D445	Viscosity @ -20, cSt		8.0	4.9	4.7	4.6	4.5	4.5
D445	Viscosity @ -40, cSt		Report	9.5	9.5	9.8	9.0	9.6
D4809	Heat of Comb.(meas),BTU/lb	Report		18870	18320	18630	18390	18510
D3338	Heat of Comb. (calc), BTU/lb	18400		18980	18680	18710	18660	18570
D5865	net Heat Comb. (meas), BTU/lb	Report		18700	18600	18440	18410	18260
D3343	Hydrogen Content, wt %	13.4		15.4	14.0	14.3	14.1	13.8
D1322	Smoke Point, mm	19.0		42.0	32.0	27.0	27.0	23.0
D1840	Naphthalenes, vol %		3.0	NR	NR	NR	NR	1.6
D130	Copper Strip Corrosion		1	1a	1a	1a	1a	1a
D3241	Thermal Stability @ 260°C							
	Tube Deposit Rating		<3	1	1	1	1	1
	Change in Pressure, mmHg		25	0	0	6	0	2
D381	Existent Gum, mg/100mL		7.0	0.6	2.8	4.6	4.6	5.2
D5452	Particulate Matter, mg/L		1.0	1.0				
	Filtration Time, minutes		15	10				
D1094	Water Reaction		1B	1	1b	1	1	1b
D5006	FSII, vol%	0.10	0.15	0.10	0.08	0.10	0.09	0.09
D2624	Conductivity, pS/m	150	600	456	292	232	239	251
D4052	API Gravity @ 60 F	37.0	51.0	55.6	49.5	48	46.6	43.8
D4052	specific gravity, g/mL	0.840	0.775	0.756	0.782	0.788	0.794	0.807
D5001	Lubricity (BOCLE), mm		Report	0.58	0.55	0.54	0.56	0.54
D5185	copper ICP, ug/L		Report	8	7	<5	10	9
D5185	zinc ICP, ug/L		Report	232	212	69	158	196
D1331	surface tension, dynes/cm		Report	23.7	24.2		24.9	25.3

note - yellow highlight indicates out of spec range

14

Table 8. Specification test results for blends with Jet A (with JP-8 Additives) F3602.

		spec min	spec max	4909(100%) FT Liquid	4909 (75%) 3602 (25%) 4938	4909 (50%) 3602 (50%) 4917	4909 (37.5%) 3602 (62.5%) 4939	4909 (25%) 3602 (75%) 4916	4909(0%) 3602(100%) 3602
SPEC/W	Workmanship		pass	pass	pass	pass	pass	pass	pass
D3242	Total Acid Num. (mg KOH/g)		0.10	0.004	0.004	0.003	0.004	0.005	0.005
D1319	Aromatics, vol %		25.0	0	4.7	10.9	14.8	18.4	23.6
D6379	Aromatics, vol % by HPLC		Report	<0.2	5.7	11.1	14.1	17.0	22.9
D3227	Mercaptan Sulfur, wt %		0.002	0.000	0.000	0.000	0.000	0.000	0.000
D4294	Total Sulfur, wt%		0.30	0.002	0.005	0.007	0.013	0.012	0.021
	Distillation D86 or D2887								
	IBP, deg C		Report	144	142	152	150	156	157
	10% recovered, deg C		205	167	170	175	175	178	182
	20% recovered, deg C		Report	177	180	185	186	187	191
	50% recovered, deg C		Report	206	208	209	210	210	211
	90% recovered, deg C		Report	256	249	249	247	244	242
	EF, deg C		300	275	273	270	269	268	264
	Residue, vol%		1.5	1.5	1.0	1.2	1.3	1.1	1.1
	loss, vol%		1.5	0.9	0.1	1	0.6	0.4	0.9
D93	Flash point, degrees C	38		45	46	49	50	50	54
D5972	Freeze Point, degrees C		-47	-51	-54	-53	-55	-54	-54
D445	Viscosity @ -20, cSt		8.0	4.9	4.6	4.8	4.8	4.8	5.0
D445	Viscosity @ -40, cSt		Report	9.5	10.5	10.3	9.8	10.3	10.6
D4809	Heat of Comb.(meas),BTU/lb	Report		18870	18760	18630	18630	17850	17840
D3338	Heat of Comb. (calc), BTU/lb	18400		18980	18850	18730	18660	18590	18490
D5865	net Heat Comb. (meas), BTU/lb	Report		18700	18390	18520	18030	18300	17980
D3343	Hydrogen Content, wt %	13.4		15.4	14.8	14.3	14.1	13.8	13.4
D1322	Smoke Point, mm	19.0		42.0	36.0	30.0	27.0	25.0	20.0
D1840	Naphthalenes, vol %		3.0	NR	NR	NR	NR	NR	0.9
D130	Copper Strip Corrosion		1	1a	1a	1a	1a	1a	1a
D3241	Thermal Stability @ 260°C								
	Tube Deposit Rating		<3	1	<1	1	<1	1	1
	Change in Pressure, mmHg		25	0	0	1	3	0	0
D381	Existent Gum, mg/100mL		7.0	0.6	0	1.8	0.0	1.4	3.4
D5452	Particulate Matter, mg/L		1.0	1.0					
	Filtration Time, minutes		15	10					
D1094	Water Reaction		1B	1	1	1	1	1	1b
D5006	FSII, vol%	0.10	0.15	0.10	0.10	0.09	0.10	0.09	0.09
D2624	Conductivity, pS/m	150	600	456	105	307	308	133	405
D4052	API Gravity @ 60 F	37.0	51.0	55.6	51.6	48.0	46.2	44.3	40.9
D4052	specific gravity, g/mL	0.840	0.775	0.756	0.773	0.788	0.796	0.805	0.821
D5001	Lubricity (BOCLE), mm		Report	0.58	0.56	0.56	0.55	0.54	0.54
D5185	copper ICP, ug/L		Report	8	<5	6	<5	<5	<5
D5185	zinc ICP, ug/L		Report	232	76	207	110	<50	145
D1331	surface tension, dynes/cm		Report	23.7		24.7		25.4	26.2

note - yellow highlight indicates out of spec range

15

Table 9. Specification test results for blends with Jet A (with JP-8 Additives) F3166.

SPEC/W	Description	spec min	spec max	4909(100%) FT Liquid	4909 (75%) 3166 (25%) 4940	4909 (50%) 3166 (50%) 4919	4909 (37.5%) 3166 (62.5%) 4941	4909 (25%) 3166 (75%) 4918	4909 (0%) 3166 (100%) 3166
SPEC/W	Workmanship		pass	pass	pass	pass	pass	pass	pass
D3242	Total Acid Num. (mg KOH/g)		0.10	0.004	0.007	0.007	0.008	0.008	0.011
D1319	Aromatics, vol %		25.0	0	3.9	8.2	10.5	11.4	17.3
D6379	Aromatics, vol % by HPLC		Report	<0.2	4.5	8.6	11.1	13.0	17.6
D3227	Mercaptan Sulfur, wt %		0.002	0.000	0.000	0.000	0.000	0.000	0.000
D4294	Total Sulfur, wt%		0.30	0.002	0.027	0.037	0.054	0.057	0.079
	Distillation D86 or D2887								
	IBP, deg C		Report	144	146	154	156	159	158
	10% recovered, deg C		205	167	171	175	176	180	184
	20% recovered, deg C		Report	177	181	185	185	189	192
	50% recovered, deg C		Report	206	209	210	210	212	213
	90% recovered, deg C		Report	256	254	251	248	250	248
	EF, deg C		300	275	274	272	271	270	269
	Residue, vol%		1.5	1.5	1.4	1.3	1.1	1.3	1.2
	loss, vol%		1.5	0.9	0.8	0.4	0.2	0.4	0.9
D93	Flash point, degrees C	38		45	46	48	49	52	55
D5972	Freeze Point, degrees C		-47	-51	-50	-47	-46	-45	-45
D445	Viscosity @ -20, cSt		8.0	4.9	4.7	5.4	5.0	5.2	5.3
D445	Viscosity @ -40, cSt		Report	9.5	10.5	10.5	11.2	10.6	11.3
D4809	Heat of Comb.(meas),BTU/lb	Report		18870	18680	18330	18510	18520	18270
D3338	Heat of Comb. (calc), BTU/lb	18400		18980	18870	18770	18720	18690	18580
D5865	net Heat Comb.(meas),BTU/lb	Report		18700	18660	18510	18450	18500	18060
D3343	Hydrogen Content, wt %	13.4		15.4	14.9	14.5	14.3	14.2	13.8
D1322	Smoke Point, mm	19.0		42.0	33.0	34.0	29.0	27.0	22.0
D1840	Naphthalenes, vol %		3.0	NR	NR	NR	NR	NR	2.4
D130	Copper Strip Corrosion		1	1a	1a	1a	1a	1a	1a
D3241	Thermal Stability @ 260°C								
	Tube Deposit Rating		<3	1	<1	1	1	1	1a
	Change in Pressure, mmHg		25	0	0	0	0	7	3
D381	Existent Gum, mg/100mL		7.0	0.6	0.2	1.2	3.2	2.4	1.4
D5452	Particulate Matter, mg/L		1.0	1.0					
	Filtration Time, minutes		15	10					
D1094	Water Reaction		1B	1	1	1	1	1	1
D5006	FSII, vol%	0.10	0.15	0.10	0.10	0.10	0.10	0.10	0.10
D2624	Conductivity, pS/m	150	600	456	215	266	212	245	284
D4052	API Gravity @ 60 F	37.0	51.0	55.6	52.2	49.2	47.8	46.3	43.4
D4052	specific gravity, g/mL	0.840	0.775	0.756	0.770	0.783	0.789	0.796	0.809
D5001	Lubricity (BOCLE), mm		Report	0.58	0.53	0.53	0.55	0.52	0.54
D5185	copper ICP, ug/L		Report	8	<5	<5	36	18	27
D5185	zinc ICP, ug/L		Report	232	75	202	61	120	127
D1331	surface tension, dynes/cm		Report	23.7		24.6		25.1	25.5

note - yellow highlight indicates out of spec range

16

3.2.1. Aromatic Content

Aromatics, as measured by ASTM D1319, are shown in Figure 2 as a function of the percent FT in the fuel blend. The linear dependence of total aromatic concentration on blend percentage can be clearly observed, which is solely due to dilution of the petroleum fuels. The linearity of this data demonstrates confidence that dilutions of petroleum fuels with FT will decrease aromatic content in a consistent manner. It can be observed that the resulting aromatic content (6.1%) for the 50% blend of the Tinker fuel (F4908) is below the current minimum specification requirement, demonstrating that the potential exists for fuels which cannot be blended to the maximum allowable volume percentage. Overall, the final aromatic content in believed to be important because these species are believed to provide swelling of elastomers and other fuel-wetted components in aircraft fuel system. Research is being conducted to determine the minimum aromatic levels required to swell o-rings.[15,18] If additional research shows that a lower minimum percentage of aromatic content can adequately provide seal swell and other FFP characteristics, then the linear functional dependence will be used to maximize the percentage of FT while maintaining levels required for the proper function of fuel system materials.
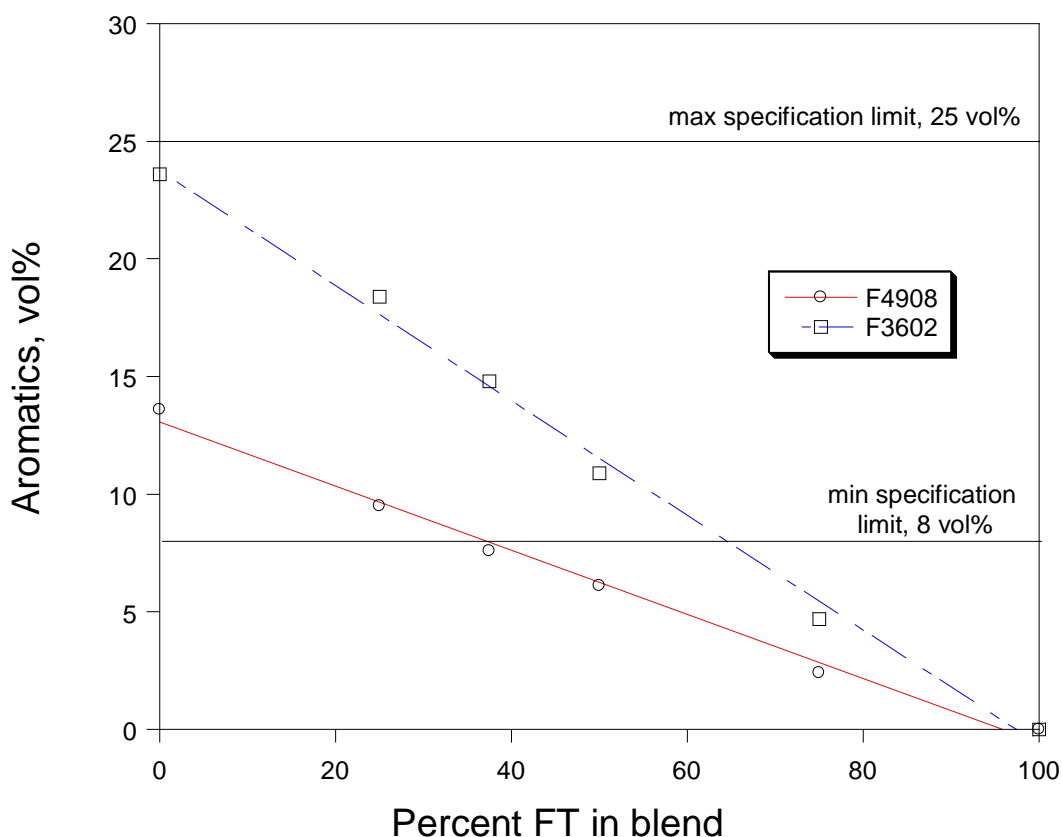
Figure 2. Dependence of aromatic content (ASTM D1319) on blend percentage of FT-derived fuel for maximum (F3602) and minimum (F4908) aromatic containing petroleum fuels.

3.2.2. Density

      Density is a critical issue for FT fuel primarily comprised of IPK, such as the one investigated in this study, since the density is significantly lower than standard petroleum-derived fuels. Figure 3 shows that density (ASTM D4052) also exhibits a linear dependence on the volume percent FT (the minimum and maximum JP-8 specification levels are noted on the figure). This dependence is rational since the base fuels are similar in nature (e.g., hydrocarbon with low heteroatom content). Therefore, the percentage of FT used in the blends may be limited if the minimum specification limit must be satisfied. For the fuels investigated, the maximum percentage of FT that can be blended with fuel 3804 to satisfy the specification limit of 0.775 g/mL is approximately 55%. The JP-8 specification allows for blending up to 50% by volume of IPK; the minimum allowable density for the neat IPK is 0.751 g/mL. Therefore, the JP-8 must have a minimum density of 0.799 g/mL to achieve the maximum allowable blend volume. Review of historical PQIS fuel procurement data is in-progress to investigate the potential for blending of petroleum-derived fuels with densities below 0.799 g/mL.
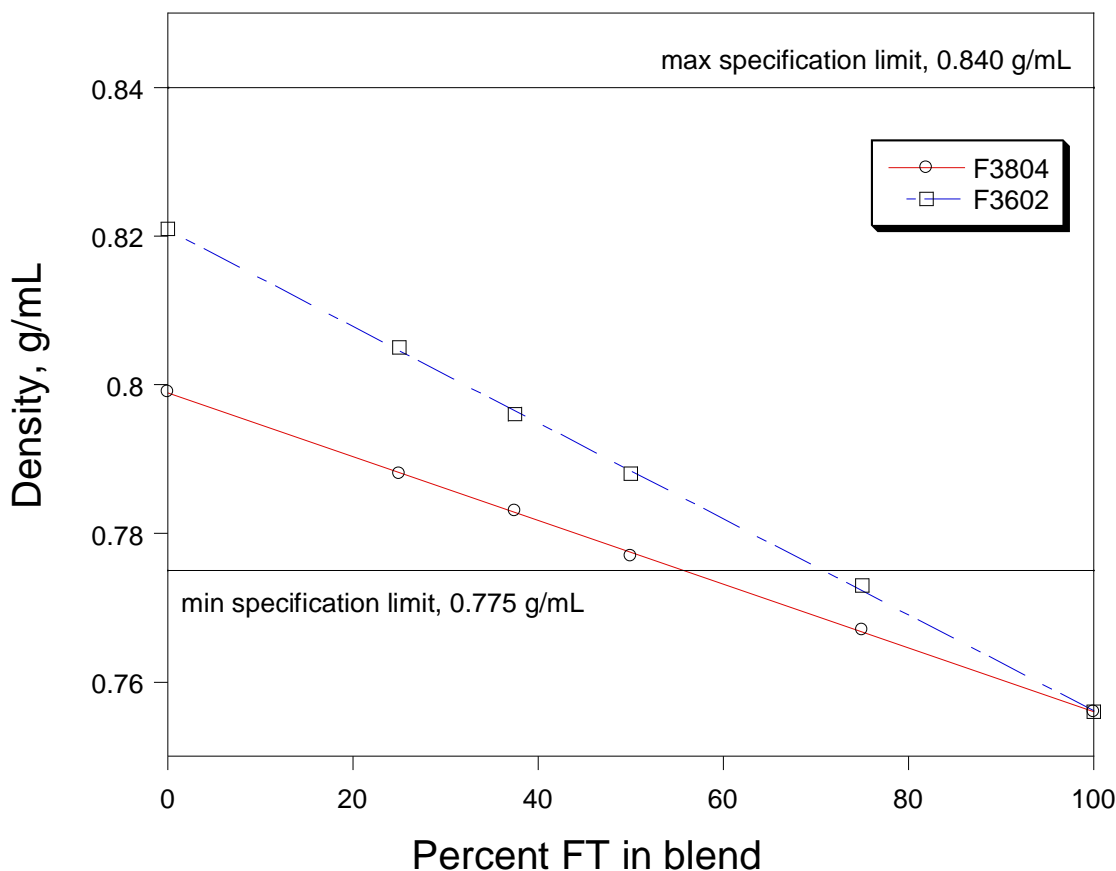
Figure 3. Dependence of density (ASTM D4052) on blend percentage of FT-derived fuel for maximum (F3602) and minimum (F3804) density petroleum fuels.

3.2.3. Hydrogen Content

The dependence of the hydrogen content (ASTM D3343) with blend percentage of FT is shown in Figure 4. The linear dependence of this property on blend percentage can be clearly observed. Both fuels show increasing hydrogen content with the addition of FT; one fuel with borderline levels of hydrogen content (F3602) is well above specification levels for hydrogen content after the addition of FT. Overall, addition of an FT-derived fuel to typical petroleum-derived fuels will render an improvement in this property.
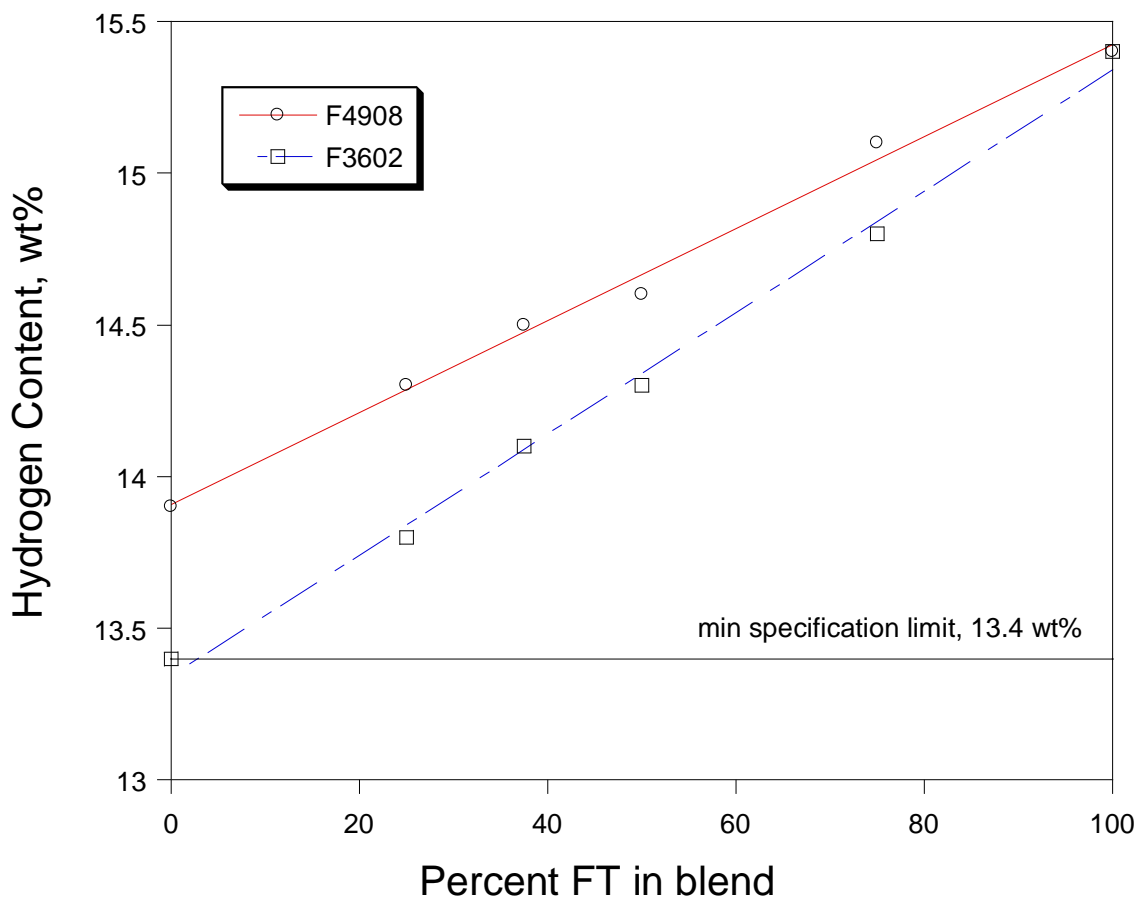
Figure 4. Dependence of hydrogen content (ASTM D3343) on blend percentage of FT-derived fuel for maximum (F4908) and minimum (F3602) hydrogen content petroleum fuels.

3.2.4. Distillation Temperature (10% Recovery)

The dependence of the distillation temperature at 10% recovery (ASTM D86) as a function of FT blend percentage is shown in Figure 5. The plot for these fuel blends demonstrates that this property is also linearly related to the percentage of FT added to the petroleum-derived fuels. The 10% recovery temperature provides guidance related to the initial volatility of the fuels and is related to the flash point. This property and the final boiling point are the only distillation temperatures which have specific requirements for JP-8 fuels; the minimum temperature allowed for a neat IPK or fuel blend is 157°C (not shown on plot).
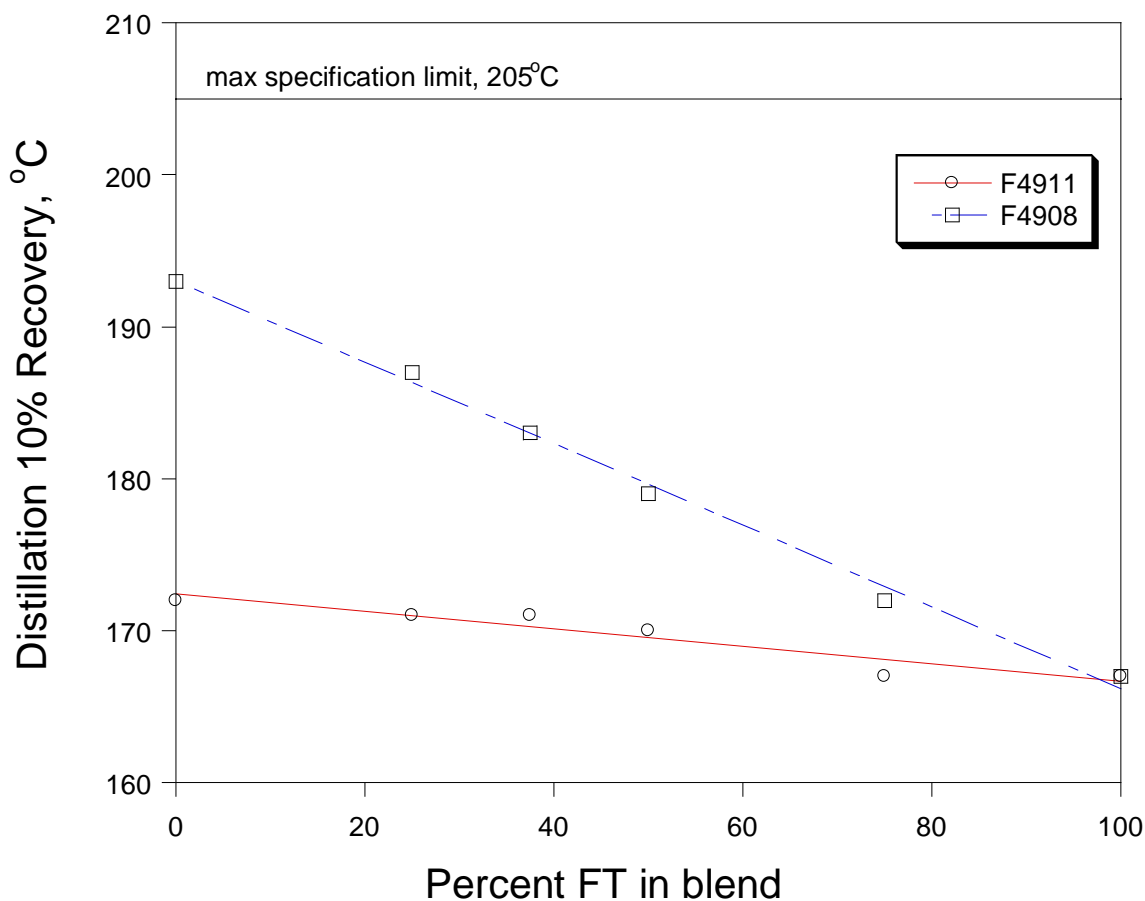
Figure 5. Dependence of distillation 10% recovery (ASTM D86) on blend percentage of FT-derived fuel for maximum (F4908) and minimum (F4911) 10% recovery temperature petroleum fuels.

3.2.5. Distillation End Point Temperature

The dependence of the distillation end point (ASTM D86) as a function of FT blend percentage is shown in Figure 6. The distillation data is consistently linear between the value for the FT fuel and that of the petroleum fuels. This dependence is reasonable since the overall distillation behavior is related to the base composition and volatility of the fuels which are blended.
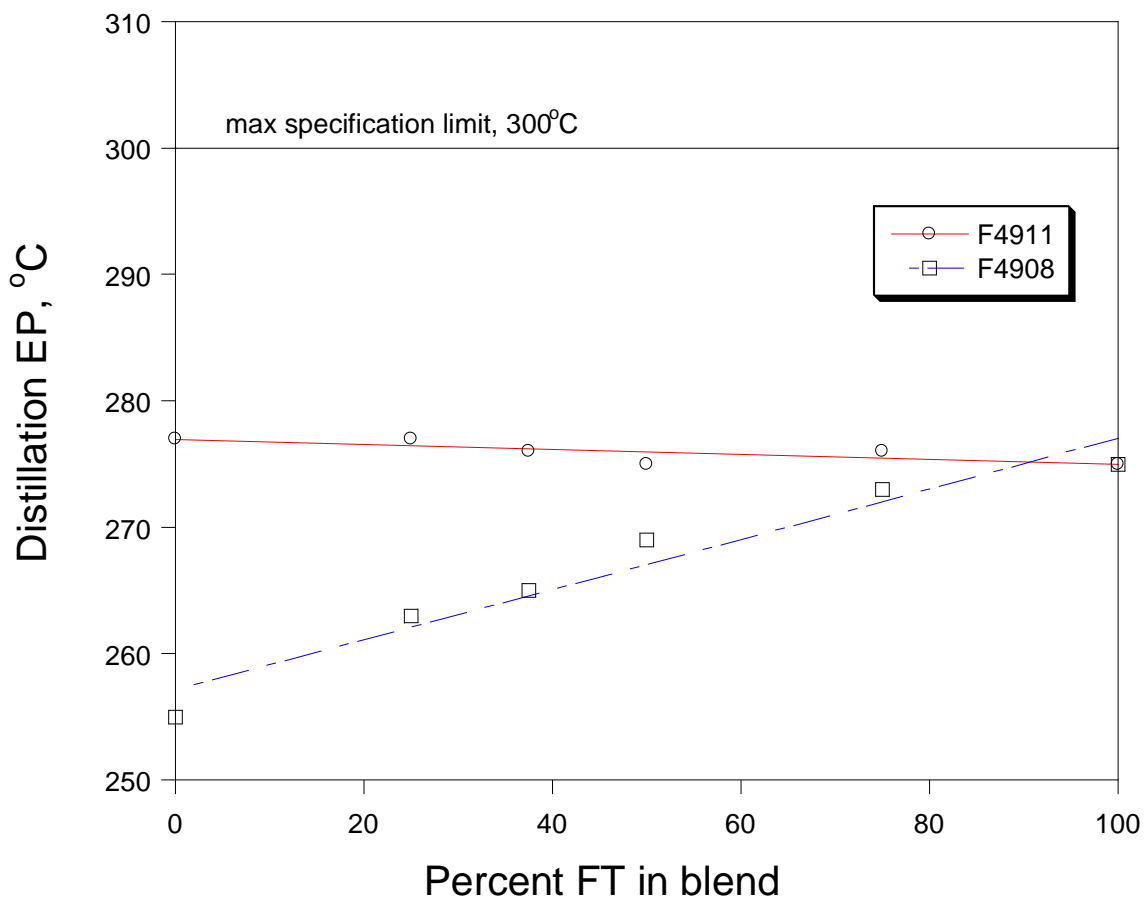
Figure 6. **Dependence of distillation end point temperature (ASTM D86) on blend percentage of FT-derived fuel for maximum (F4911) and minimum (F4908) end point temperature petroleum fuels.**

3.2.6. Flash Point

The dependence of the flash point (ASTM D93) as a function of FT blend percentage is shown in Figure 7. There is a linear dependence of the flash point on percentage of FT blended into the petroleum fuels. This dependence most likely occurs since the FT has a similar volatility and molecular weight range to typical aviation fuels; significant changes in the relative distribution could render non-linear behavior. It may be possible to formulate the FT fuel such that is possible to elevate low flash point petroleum fuels or to moderate higher flash point fuels (such as F4908). The JP-8 specification has an allowable flash point range for neat IPK and fuel blends of 38-68°C, which would prevent significant changes to volatility compared to that for typical fuels.
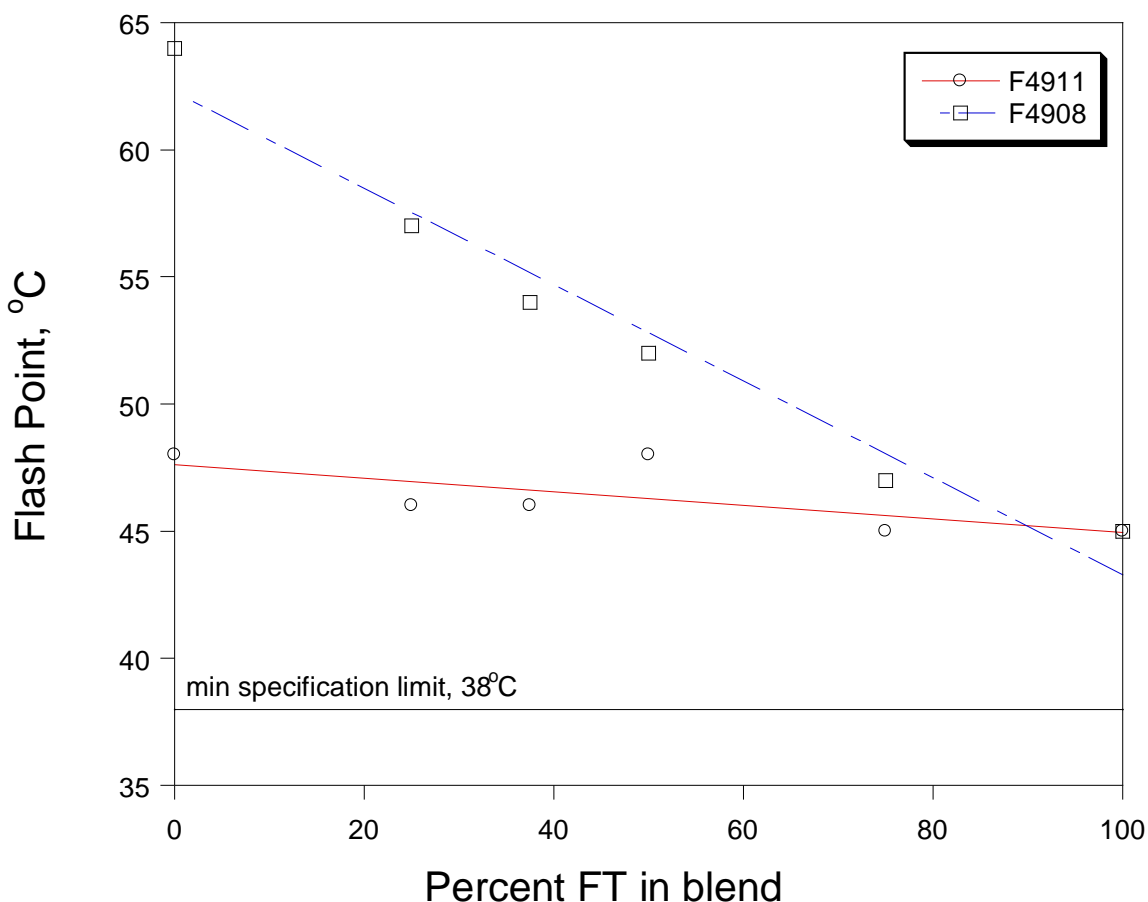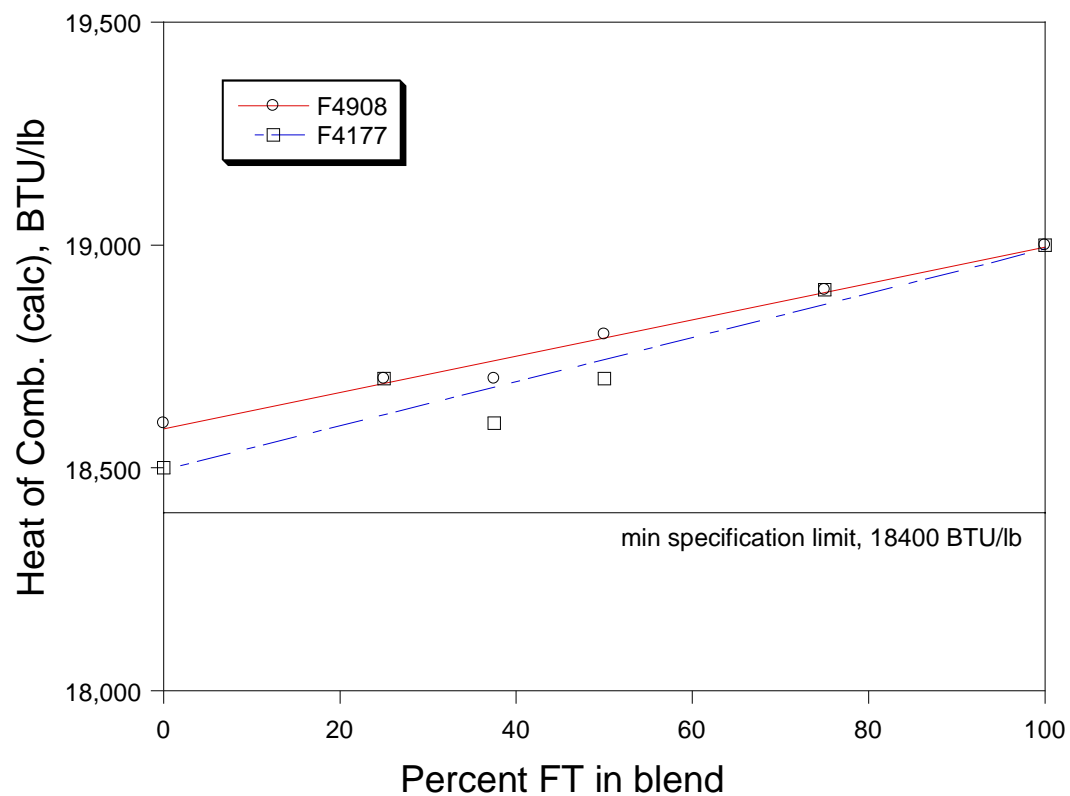

Figure 7. Dependence of flash point (ASTM D93) on blend percentage of FT-derived fuel for maximum (F4908) and minimum (F4911) flash point petroleum fuels.

3.2.7. Freeze Point

The dependence of the freeze point (ASTM D5972) as a function of FT blend percentage is shown in Figure 8. The freeze point for petroleum/FT fuel mixtures, with respect to volume percent FT, also follows a linear trend. Fuel F3166 is initially above the JP-8 specification limit because it is a Jet A fuel (maximum freeze point is -40°C); however, it satisfies the freeze point requirement with the addition of at least 50 volume % FT fuel. Thus, it may be possible to improve some of the properties of Jet A or JP-8 fuels such that they can satisfy previously unmet specifications. The freeze point results differ slightly from the blending studies performed with the aforementioned SMDS fuel, which showed a depression in freeze point below that for the linear dependence.[10] It is believed that the results from the previous study can be attributed to the inherent differences of the SMDS with the IPK used herein. As previously discussed, the SMDS was a very narrow cut kerosene with a high *n*-alkane/*iso*-alkane ratio. This significant difference compared to typical aviation fuels may provide non-ideal behavior during mixture.
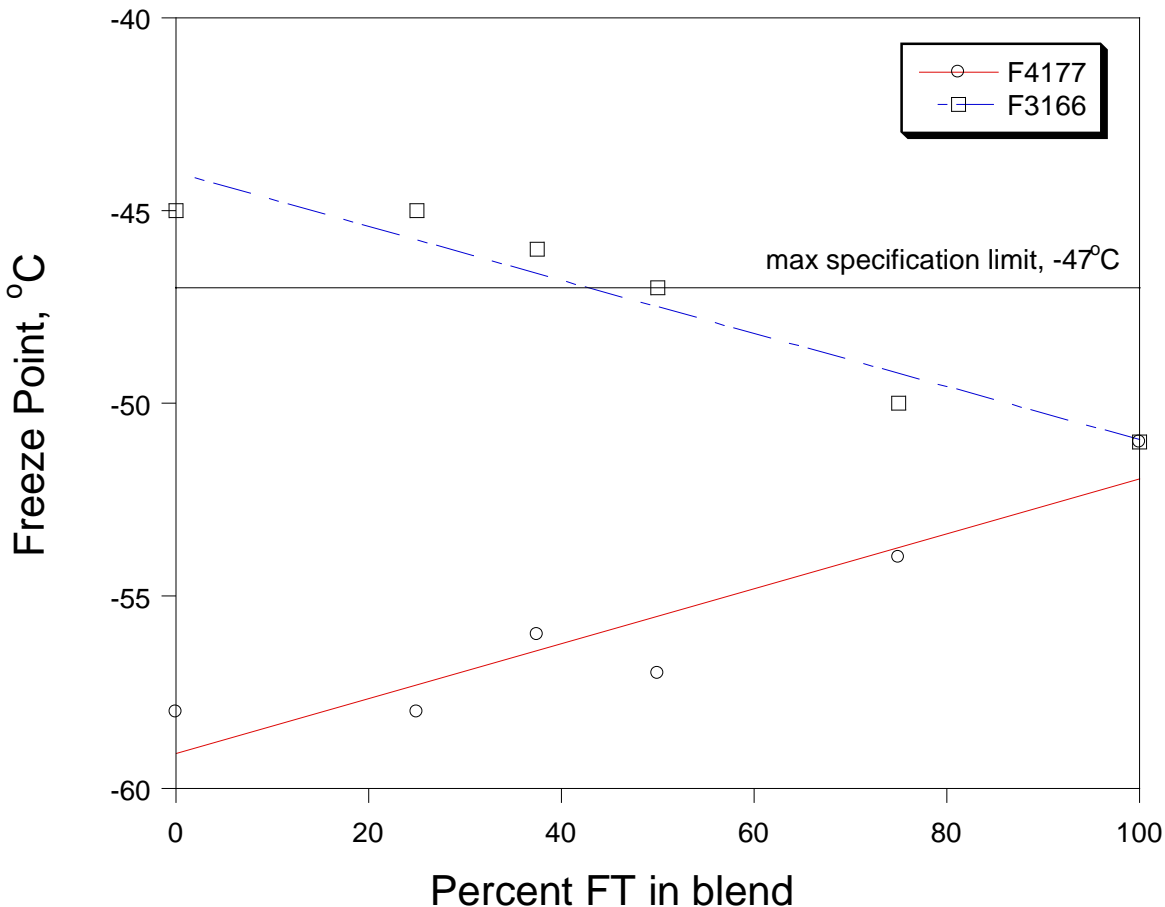
Figure 8. Dependence of freeze point (ASTM D5972) on blend percentage of FT-derived fuel for maximum (F4177) and minimum (F3166) freeze point temperature petroleum fuels.

3.2.8. Measured and Calculated Heat of Combustion

The measured heat of combustion (ASTM D4809) and calculated heat of combustion (ASTM D3338) as a function of FT blend percentage are shown in Figure 9 and 10, respectively. As Figure 9 shows, although there appears to be a few outlying points (which are most likely due to experimental error), the overall trend of the measured heat of combustion data is linear. The calculated heat of combustion data is also linear for the fuel blends. The linear dependence is most likely due to dilution theory, as the overall energy content on a mass basis is related to the overall composition. It should be noted that the use of ASTM D3338 for calculating the heat of combustion of non-petroleum derived fuels may be limited. The correlation is purely empirical and may be prone to inaccuracy when used to calculate values for fuel types which differ from the control set used in the method development. Additional study should be performed to verify the applicability and limitations of using ASTM D3338 for IPK fuels and blends. Further discussion on the measured heat of combustion values is provided in Section 3.3.7.
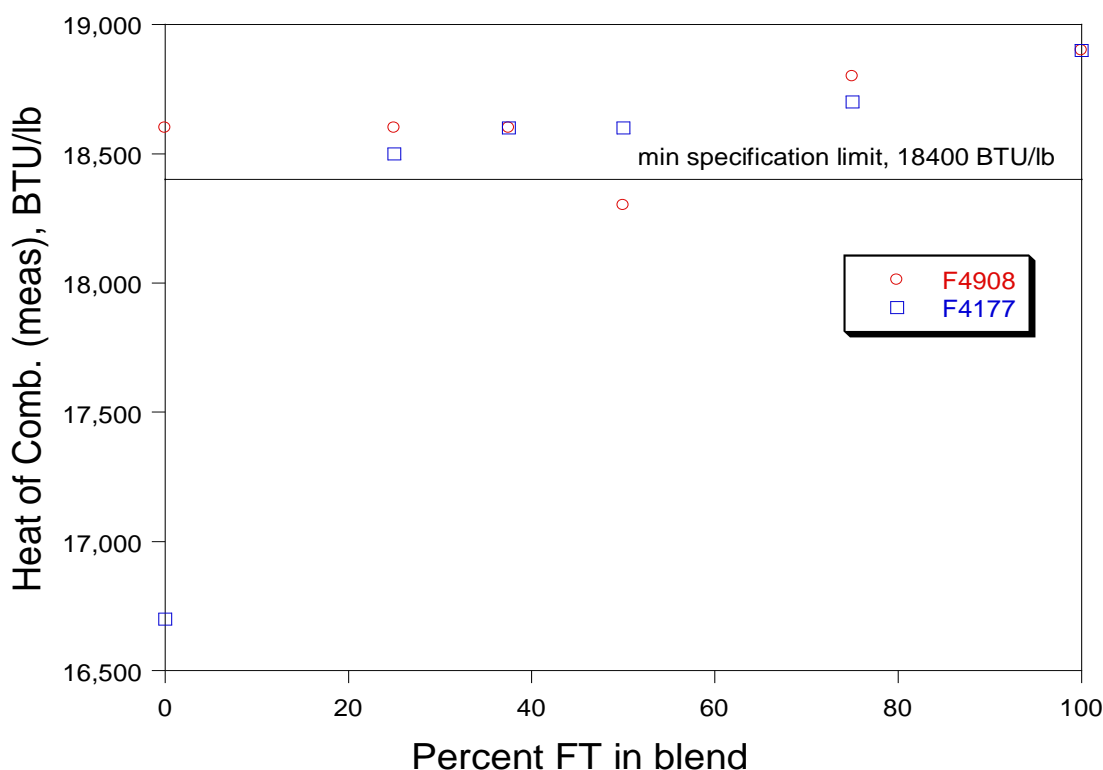

Figure 9. Dependence of the measured heat of combustion (ASTM D4809) on blend percentage of FT-derived fuel for maximum (F4908) and minimum (F4177) measured heat of combustion petroleum fuels.

24

Figure 10. Dependence of the calculated heat of combustion (ASTM D3338) on blend percentage of FT-derived fuel for maximum (F4908) and minimum (F4177) calculated heat of combustion petroleum fuels.

3.2.9. Total Acid Number (TAN)

The measured total acid number (TAN) (ASTM D3242) as a function of FT blend percentage is shown in Figure 11. The TAN was found to vary linearly with FT blend percentage, primarily due to dilution theory. It should be noted that measurements for typical JP-8 fuels very rarely exhibit TAN values close to the specification limit of 0.10 mg KOH/g.
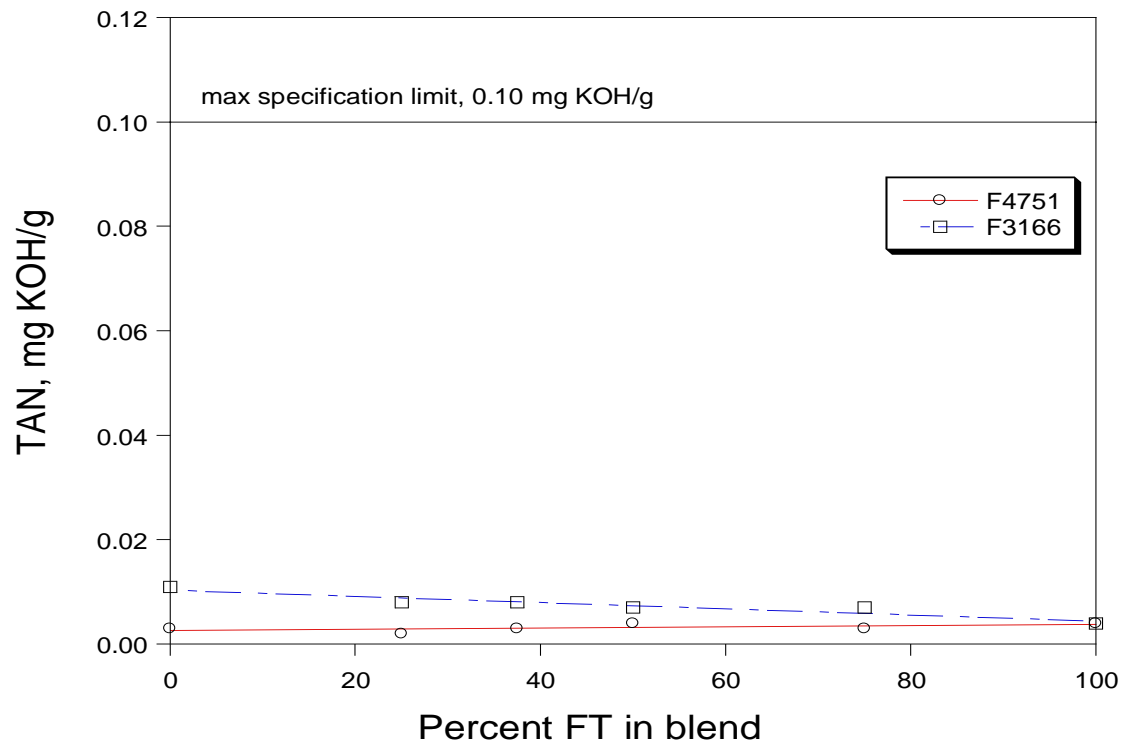
Figure 11. Dependence of the total acid number (ASTM D3242) on blend percentage of FT-derived fuel for maximum (F3166) and minimum (F4751) total acid number petroleum fuels.

3.3. Non-Specification Tests Results

There are several fuel properties and "Fit-for-Purpose" performance characteristics which are not explicitly evaluated within the JP-8 fuel specification. For petroleum-derived fuels, these properties are typically acceptable provided the fuel satisfies all of the required property specifications. This most likely occurs since the allowable ranges for the required specification properties were initially determined such that the formulated fuels satisfied all primary and secondary operability requirements. Examples of such properties include the surface tension and dielectric constant of the fuel. Blending with non-petroleum derived fuels, such as the IPK herein, may result in variance of these non-specification properties outside of acceptable ranges for legacy and next-generation aircraft platforms. The following sections discuss selected testing which was performed to preliminarily investigate the effect of blending synthetic IPK on certain non-specification requirements.

3.3.1. Hydrocarbon Type Analyses

ASTM method D2425-93, "Hydrocarbon Types in Middle Distillates by Mass Spectrometry," uses a series of analyses to determine the levels of various chemical classes within fuels.[21] Each fuel is initially analyzed for aromatic hydrocarbon content by ASTM method D6379 in which normal-phase high performance liquid chromatography (HPLC) with refractive index detection is used. The aromatics are eluted from a cyano column (4.6 x 150 mm) with hexanes as the mobile phase; standards containing mono- and di-aromatics are used to calibrate the HPLC (Agilent Model #1100). The refractive index peak areas are used to quantify the volume percent of mono- and di-aromatics while the saturated hydrocarbons are calculated via difference. In the second part of the D2425 method, the fuel samples diluted in hexanes are separated by the same HPLC method and the saturates and aromatics fractions are collected. The two fractions are analyzed by gas chromatography/mass spectrometry (GC-MS). Extracted ion areas, as required by method D2425, are obtained from the mass spectral data through a data analysis macro. The volume percentages from HPLC and these extracted ion areas are used to calculate the percentages of the various classes within the fuel.

The hydrocarbon type analyses results for the base fuels are shown in Table 10. The FT fuel is composed of paraffins (normal and *iso-*) with <1% cycloparaffins and aromatics. Typical JP-8 samples contain approximately 50-60% paraffins (~15-20% *n*-alkanes), 20-30% cycloparaffins, and 15-20% aromatics (about 1-2% of which are di-aromatics). Hydrocarbon type will vary linearly with blending as this process is solely a function of dilution. However, blending large volumes of FT fuel will alter the hydrocarbon type distribution to be inherently different than a typical petroleum-derived fuel, which may affect FFP properties. The Jet A and JP-8 fuels would be reduced in the concentration of several constituents, particularly, aromatic, cycloparaffin and multi-ring aromatic content. This dilution could have considerable impact on beneficial fuel characteristics such as reductions in emissions, lowering of freeze point, and an increase in hydrogen content. However, the reduction in aromatics (as mentioned earlier) may affect other properties, such as elastomer swell, additive solubility and density, in a negative or non-advantageous way.

Table 10. Hydrocarbon Type Analysis by ASTM D2425.

	F4909 FT	F3166 Jet A w/JP-8 additives	F3602 JetA w/JP-8 additives	F3694 JetA w/JP-8 additives	F3804 JP-8	F4177 JP-8	F4751 JP-8	F4908 JP-8	F4911 JP-8
Summarized D2425 (vol%)									
Paraffins	>99	58.9	45.8	53.3	61.6	51.3	59.6	55.8	56.0
Cycloparaffins	<1	15.3	16.1	22.9	14.0	18.0	14.5	22.2	17.4
Dicycloparaffins	<1	7.5	13.6	7.9	4.1	11.8	5.9	8.8	9.6
Tricycloparaffins	<1	<1	1.5	<1	<1	1.6	<1	<1	<1
Alkylbenzenes	<0.2	10.6	13.7	10.5	14.4	9.3	12.0	8.0	9.3
Indan and Tetralins	<0.2	4.3	8.1	3.5	3.4	6.7	6.3	3.2	5.5
Indenes CnH2n-10	<0.2	0.2	<0.2	<0.2	<0.2	<0.2	<0.2	0.3	<0.2
Naphthalene	<0.2	0.2	<0.2	<0.2	<0.2	<0.2	<0.2	0.2	<0.2
Naphthalenes	<0.2	2.2	0.9	1.6	2.1	1.0	1.2	1.2	1.1
Acenaphthenes	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Acenaphthylenes	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Tricyclic Aromatics	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Total	100	100	100	100	100	100	100	100	100
D6379 (vol%)									
Monoaromatics	<0.2	15.1	21.9	14.1	17.8	16.1	18.2	11.5	14.9
Diaromatics	<0.2	2.5	1.1	1.8	2.2	1.2	1.4	1.4	1.3
Total Aromatics	<0.2	17.6	23.0	15.9	20.0	17.3	19.6	12.9	16.2
Total Saturates	100	82.4	77.0	84.1	80.0	82.7	80.4	87.1	83.8

3.3.2. Normal Alkanes Analyses

The paraffinic content of the fuels was further characterized by quantification of the normal alkanes using a gas chromatograph combined with a mass spectrometer (GC-MS) and a flame ionization detector (GC-FID). The GC-MS and GC-FID systems are calibrated with standards containing C_7-C_{19} normal alkanes and an internal standard. Calibration curves are generated by obtaining response factors between the area responses for the compounds of interest and the internal standard. Samples are diluted such that concentrations of the components are in the linear calibration range. Each sample is diluted to at least two different concentration ranges with the higher concentration components quantified by GC-MS. The GC-MS quantitation involves the extracted ion areas of the primary characteristic ions, which provides baseline separation of the normal alkanes from other fuel components. The lower concentration normal alkanes are already baseline separated from the fuel matrix and can be quantified directly by GC-FID.

The concentrations of normal alkanes for the various fuels are shown in Table 11. The FT fuel used has a total concentration of normal alkanes similar to that of the average concentrations for the petroleum-derived fuels (17.6% total). Although the distribution of the *n*-alkanes in the FT fuel was skewed toward lower molecular weight (highest concentration at decane (C_{10}) versus undecane (C_{11})) the distillation range was within the JP-8 specifications. The flash point was 45°C for the FT fuel, as opposed to an average flash point of 53°C for the eight petroleum derived fuels. The dependence of the total *n*-alkane concentration on blending will be linear solely due to dilution theory. Overall, blending of an FT fuel with a similar total *n*-alkane content and molecular-weight range for a petroleum-derived fuel should result in minimal, or predictable, effect on the properties which are highly dependent on these components, such as the freeze point.

Table 11. Concentration of Normal Alkanes in Fuels.

	F4909 FT	F3166 Jet A w/JP-8 additives	F3602 Jet A w/JP-8 additives	F3694 Jet A w/JP-8 additives	F3804 JP-8	F4177 JP-8	F4751 JP-8	F4908 JP-8	F4911 JP-8
Normal Alkane (weight %)									
n-Heptane	0.14	0.082	0.028	0.069	0.13	0.077	0.11	0.029	0.12
n-Octane	1.32	0.33	0.40	0.45	0.44	0.23	0.37	0.10	0.48
n-Nonane	2.60	1.27	0.98	1.69	2.22	0.64	1.17	0.39	1.47
n-Decane	3.23	2.71	1.53	3.04	4.72	1.74	3.15	2.13	2.33
n-Undecane	3.18	4.24	3.90	3.77	5.10	2.89	3.83	5.21	2.66
n-Dodecane	2.46	4.01	3.37	3.24	4.28	2.74	3.41	4.69	2.30
n-Tridecane	1.94	3.58	2.54	2.91	3.56	2.04	2.77	3.49	1.93
n-Tetradecane	1.18	2.79	1.47	1.85	2.30	0.97	1.87	1.77	1.40
n-Pentadecane	0.70	1.55	0.61	0.84	0.82	0.39	0.90	0.57	0.77
n-Hexadecane	0.35	0.45	0.16	0.25	0.15	0.14	0.27	0.12	0.32
n-Heptadecane	0.088	0.13	0.055	0.092	0.029	0.074	0.087	0.035	0.16
n-Octadecane	0.010	0.031	0.012	0.027	0.006	0.031	0.023	0.009	0.072
n-Nonadecane	0.002	0.011	0.005	0.012	0.002	0.016	0.008	0.002	0.025
Total	**17.2**	**21.2**	**15.1**	**18.2**	**23.8**	**12.0**	**18.0**	**18.5**	**14.0**

3.3.3. Polars Analyses by HPLC

Naturally occurring polar compounds, molecules which contain heteroatoms, are typically found in petroleum-derived aviation fuels. These compounds have been related to the thermal-oxidative stability of the fuels as well as to potentially contribute to material compatibility and elastomer swell issues.[22-25] Identification and quantitation of these compounds can provide insight regarding relative performance of the fuels within aircraft fuel systems. Therefore, the polar species in the various fuels were separated and quantified using an HPLC with a diode array detector (UV wavelength of 254 nm) with a slow gradient of hexanes followed sequentially by isopropanol and methanol. The detector used was a diode array detector at a UV wavelength of 254 nm. Since phenolic compounds have been found to comprise a significant position of polar compounds within typical fuels, the HPLC was calibrated with standards containing a mixture of phenolic compounds. The standards used were prepared to approximate the average phenolic compound composition of the JP-8 and Jet A fuels. Five standards were prepared which spanned the linear range of the instrument. 100-μL injections of the standards and samples were analyzed.

The FT fuel did not contain detectable level of polar compounds, as shown in Table 12. This result was plausible as the fuel was prepared via indirect synthesis using a cobalt catalyst which would primarily produce C_1-C_2 alcohols; these would be effectively removed during distillation. As a result, blending of the FT fuel should reduce the level of polars linearly. This could render significant improvements in the thermal stability of the fuel[1-2]; however, the storage stability would be reduced which will most likely require the addition of artificial antioxidants during fuel delivery and storage.

Table 12. Polars in Fuels by HPLC.

	F4909 FT	F3166 Jet A w/JP-8 additives	F3602 Jet A w/JP-8 additives	F3694 Jet A w/JP-8 additives	F3804 JP-8	F4177 JP-8	F4751 JP-8	F4908 JP-8	F4911 JP-8
Polars (mg/L)	< 20	530	120	650	160	400	160	290	290

3.3.4. Surface Tension

Surface tension of the neat fuels and blends was measured with a Fisher Surface Tensiomat, Model 21 (ASTM D1331). In this method a platinum-iridium ring of known dimensions is suspended from a counter-balanced lever-arm. The arm is clamped to a stainless steel wire that holds it horizontal by torsion. The ring is initially immersed in a liquid. The arm and ring are raised by increasing the torsion in the wire. The tensiomat measures the force in dynes/centimeter required to pull the ring free from the surface film of the liquid (apparent surface tension). The Absolute surface tension is calculated by multiplication with a correction factor. The tensiomat is factory-calibrated, which is verified by analyzing a liquid of known surface tension (i.e., acetone). The surface tension results are included with the specification test data (see Tables 2-9).

The FT fuel has a lower surface tension than all the other fuels tested, but only by approximately 1-3 dynes/cm (petroleum fuel surface tension range 25.3 to 26.2 dynes/cm). Blending of the FT fuel, with the other fuels, resulted in a slight decrease in surface tension. The implications of this small difference and reduction during blending upon fuel system and combustor performance requires further review and investigation.

3.3.5. Sulfur Speciation Analysis

Sulfur speciation of each fuel was performed to quantify the various classes of compounds typically found in aviation fuels. Quantitation was performed using a gas chromatograph coupled with an atomic emission detector (GC-AED). During analysis, a 300 μL sample of fuel was spiked with 10 μL of a sulfur standard in kerosene as an internal standard. Results from the sulfur speciation analysis by chemical class are shown in Table 13. The FT fuel contains no sulfur compounds due to the removal of the sulfur during the synthesis gas production process. Therefore blending of the IPK with the petroleum derived fuels will result in reduced sulfur concentration. As various sulfur species can both negatively (emission, particulate matter) and positively (lubricity) affect fuel properties, the overall effect of reduced sulfur concentration on fuel blends will be dependent on the characteristics of the base petroleum-derived fuel.

Table 13. Sulfur Speciation in Fuels by GC-AED.

Sample #	Thiols, sulfides & disulfides (ppm by wt)	Thiophenes (ppm by wt)	Benzo-thiophenes (ppm by wt)	Dibenzo-thiopenes (ppm by wt)	Total Sulfur (ppm by wt)
F3804	285	<10	295	<10	594
F4751	284	<10	137	15	445
F3602	159	<10	35	<10	203
F3166	481	26	335	24	866
F4911	504	15	231	16	766
F3694	1050	23	408	480	1970
F4177	895	151	429	10	1490
F4908	642	30	245	<10	920
FT Fuel F4909	<10	<10	<10	<10	<10

3.3.6. Scanning Brookfield Viscosity

The low-temperature viscosity behavior of aviation fuels is important due to the need for reliable pumpability and flowability at the extremely low temperatures experienced during flight. Therefore, neat fuels and blends were evaluated for low temperature flow properties using scanning Brookfield viscometry. In this technique, a stationary sample test tube (stator) containing the fuel sample and a metal rotor suspended in the center are connected to a viscometer head. The stator and rotor are lowered into a temperature-programmable methanol bath. The head provides the torque to the rotor to maintain a constant velocity as the temperature in the bath is lowered from –20 to –70°C at a rate of 5°C per hour.

The viscometer torque vs. viscosity behavior is calibrated with a mineral oil standard having measured viscosities (in centipoises units, cP) at five temperatures from –20 to –45°C. The calibration is performed by first obtaining the slope, m, and intercept, b, of the relationship between viscosity (η) and temperature (T) from the MacCoull, Walther, Wright equation as follows:

$$\log[\log(\eta + 0.7)] = m(\log T) + b \tag{1}$$

The torque of the mineral oil is then measured over the temperature range from –20 to -45°C under a cooling rate of 2°C per hour. The viscosity is calculated at each temperature and a linear relationship between torque and viscosity is generated. The slope and intercept of this linear relationship are used to convert torque measurements to viscosity measurements. Dynamic viscosity curves as a function of temperature can then be generated.

While the dynamic viscosity curves give accurate indications of the relative behavior of fuels over a range of temperatures, kinematic viscosity in centistokes (cSt) units is the current standard for evaluating fuel viscosity at a specific temperature. The kinematic viscosity measurements at –40°C generated by the AFPA Laboratory (ASTM D445) are used to anchor the dynamic viscosity measurements to allow for comparison of the measured fuel viscosities between the two techniques. An accurate measurement of fuel density is required to convert between the dynamic and kinematic viscosities. Therefore, density measurements for each of the fuels were performed at –40°C using a pycnometer. The –40°C viscosities and densities are shown in Table 14. The densities for all neat fuels and for three of the corresponding blends were measured to verify linearity with blending. Remaining density values were estimated assuming linearity dependence with blending.

The dynamic viscosity curves for the FT fuel, fuel F4751, and blends of the two fuels are shown in Figure 12 as representative viscosity behavior. For neat JP-8 and Jet A fuels, the viscosity gradually increases with decreasing temperature until there is a sharp rise in viscosity. This sharp increase or "knee" in the viscosity curve occurs at the cloud point of the fuel. The cloud point is the temperature at which crystals begin forming on cooling and is usually a few degrees below the freezing point. The FT fuel displays a more gradual increase in viscosity after the cloud point. The viscosity curves of the fuel blends show behavior that is between the neat fuel and FT. It also appears that the FT fuel has viscosities similar to that of the JP-8 from -20°C to their cloud points. The dynamic viscosity curves for the remaining JP-8 and Jet A fuels/blends are shown in Appendix I.

Table 14. Dynamic and kinematic viscosities at -40°C.

Fuel ID	-40°C Kinematic viscosity (cSt)	-40°C Density	-40°C Dynamic viscosity (cP)
FT F4909	9.5	0.7934	7.5
Jet A F3166 w/ JP-8 additives	11.3	0.8475	9.6
F4918 (25% F4909/ 75% F3166)	10.6	0.834	8.8
F4919 (50% F4909/ 50% F3166)	10.5	0.820	8.6
Jet A F3602 w/ JP-8 additives	10.6	0.8594	9.1
F4916 (25% F4909/ 75% F3602)	10.3	0.843	8.7
F4917 (50% F4909/ 50% F3602)	10.3	0.826	8.5
Jet A F3694 w/ JP-8 additives	9.6	0.8447	8.1
F4920 (25% F4909/ 75% F3694)	9.0	0.832	7.5
F4921 (50% F4909/ 50% F3694)	9.5	0.819	7.8
JP-8 F3804	8.3	0.8349	6.9
F4914 (25% F4909/ 75% F3804)	8.7	0.825	7.2
F4915 (50% F4909/ 50% F3804)	9.0	0.814	7.3
JP-8 F4177	10.2	0.8515	8.7
F4926 (25% F4909/ 75% F4177)	10.0	0.837	8.4
F4927 (50% F4909/ 50% F4177)	10.5	0.822	8.6
JP-8 F4751	9.9	0.8425	8.3
F4912 (25% F4909/ 75% F4751)	10.2	0.830	8.5
F4913 (50% F4909/ 50% F4751)	9.7	0.8185	7.9
F4929 (37.5% F4909/ 62.5% F4751)	9.6	0.824	7.9
F4928 (75% F4909/ 25% F4751)	9.5	0.806	7.7
JP-8 F4908	11.1	0.8454	9.4
F4922 (25% F4909/ 75% F4908)	10.5	0.832	8.7
F4923 (50% F4909/ 50% F4908)	10.8	0.8201	8.8
JP-8 F4911	9.4	0.8452	7.9
F4924 (25% F4909/ 75% F4911)	9.4	0.832	7.8
F4925 (50% F4909/ 50% F4911)	9.3	0.8199	7.6

Note: Densities reported to 3 decimal places were calculated.
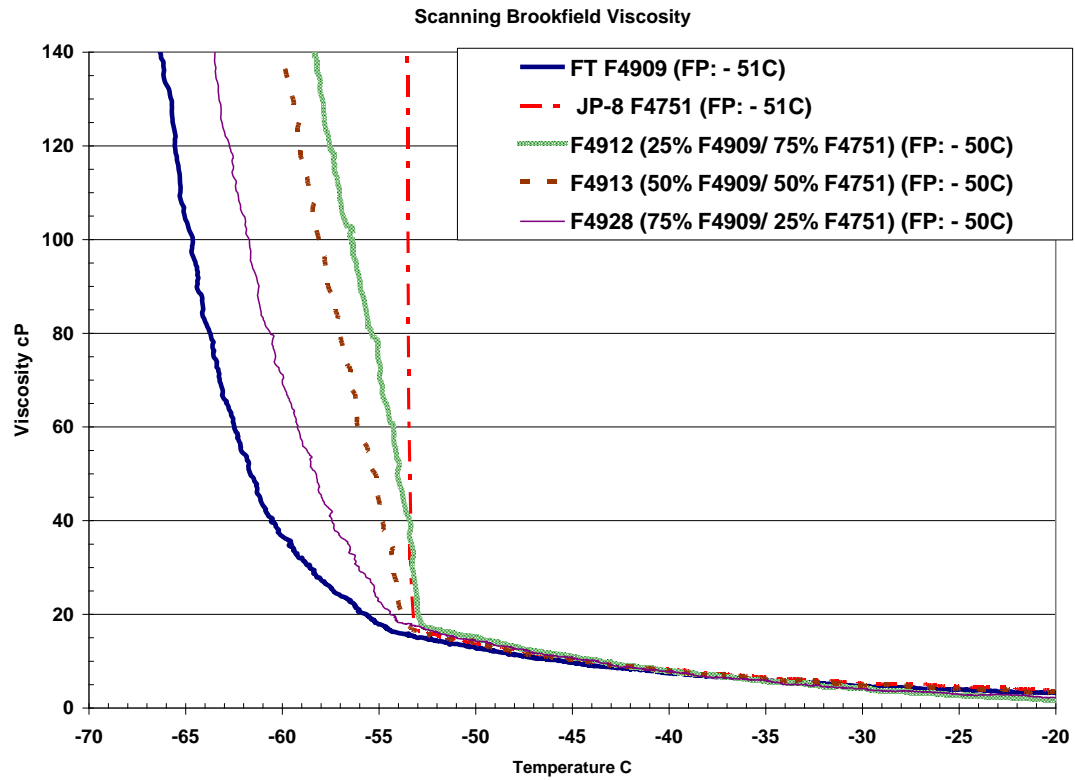
Figure 12. Dynamic Viscosities as a function of temperature for FT-derived fuel, petroleum-derived JP-8 and fuel blends.

3.3.7. Measured Heat of Combustion Values

The heat of combustion of a fuel is a critical property as it relates to the amount of energy which can be provided to a propulsion system. There are various methods to acquire the heat of combustion value. The AFPA specification test method of preference is currently ASTM D3338, which calculates the heat of combustion from four of the specification tests results: aromatic content, sulfur content, distillation range and density. As stated previously, the correlation used in D3338 is purely empirical and may be prone to inaccuracy when used to calculate values for fuel types which differ from the control set used in the method development. Therefore, ASTM D4809 was used to provide direct measurements of the heat of combustion using bomb calorimetry (see Figure 9). While these calorimeter measurements showed similar trends as the calculated values, there were sufficient outliers and non-linearity with respect to blend concentration to warrant an additional set of measurements by an outside laboratory. Galbraith Laboratories, Knoxville, TN, was contracted to provide a secondary set of heat of combustion measurements for the fuel blends. This measurement was performed using ASTM D5865, which reports a heat of combustion value in terms of *gross* heat of combustion. A more appropriate comparison to typically reported data (from the AFPA) would be that of *net* heat of combustion, which is reported in Figure 13 (a-h). The gross heat of combustion was changed to the net value using a relationship provided in ASTM D5865 which involves hydrogen content which accounts for water produced remaining in the vapor (net) rather than releasing additional heat and forming liquid.

It can be clearly observed that there are large variances in the absolute values for the heat of combustion measurements. Overall, the dependence of the heat of combustion with blending appears to be linear, with the calculated values from D3338 being slightly higher than the measured values. The measured values using D4809 (AFPA) were in better agreement with the calculated values for most cases; there were a few outliers for these measurements. It is apparent that some of the measurements are not consistent with the expected trend and are below the minimum JP-8 specification limit. These inconsistencies were attributed to experimental error during the analysis. The implication of this data set and incorporating the use of D3338 for evaluation of SPK fuels and blends requires additional review.
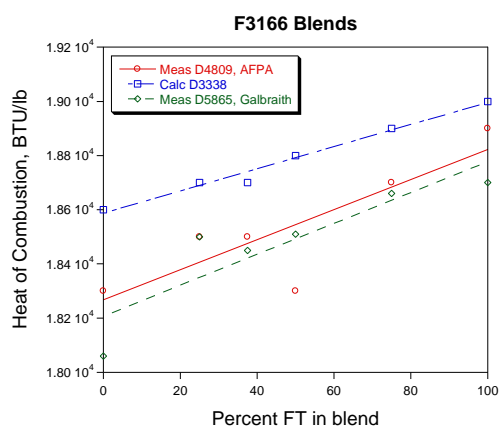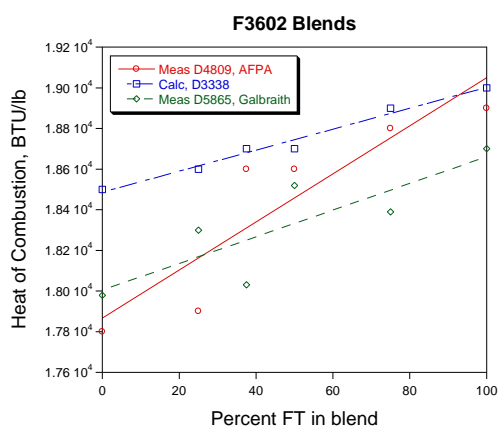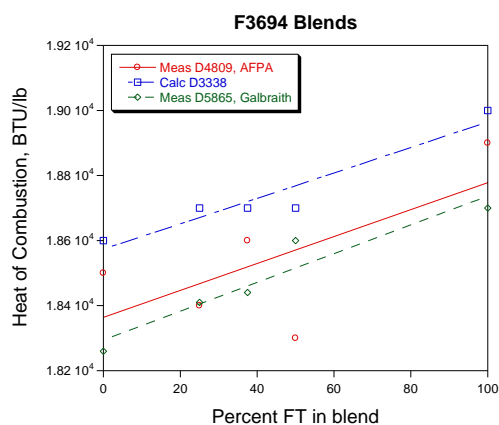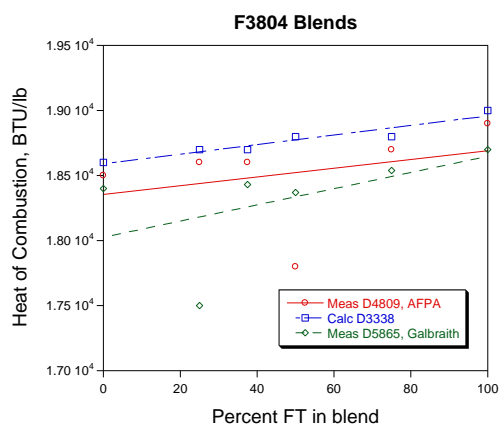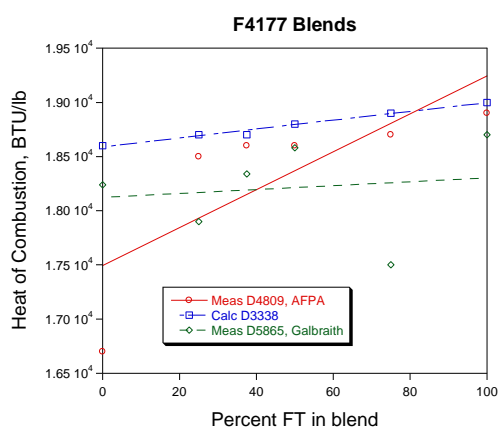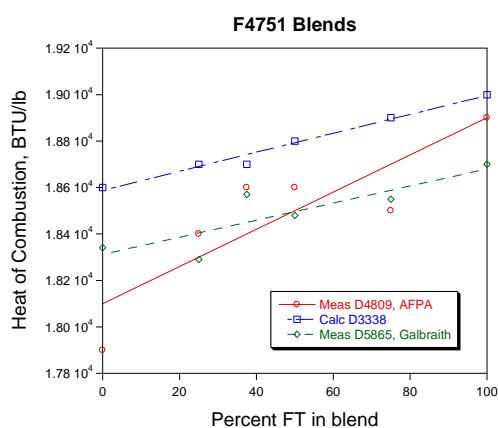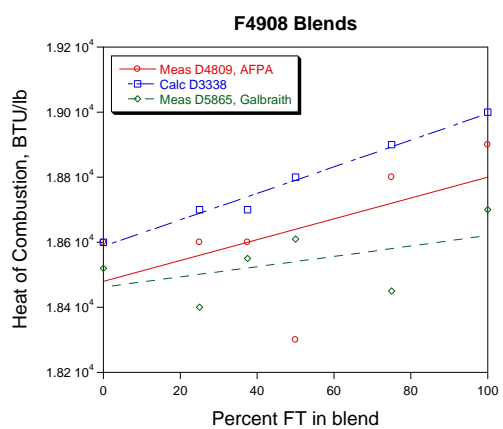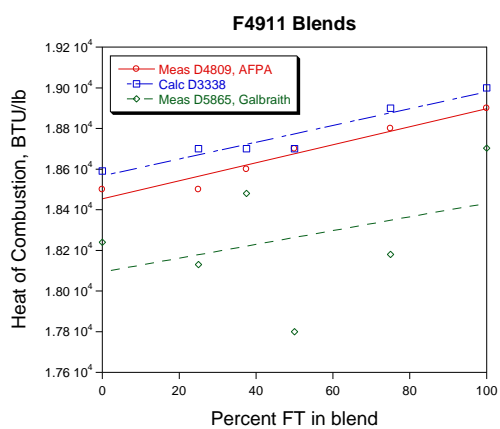
Figure 13. a-f. Heat of combustion results for blends of petroleum fuels and FT.

Figure 13. g-h. Heat of combustion results for blends of petroleum fuels and FT.

3.4. Thermal Stability via QCM

The quartz-crystal microbalance (QCM, see Figure 14) has been used extensively to study jet fuel thermal stability and prescreen the thermal oxidative impact of various jet fuel additives.[24-26] The QCM has the capability to monitor both headspace oxygen and carbon deposition *in-situ* during fuel thermal stressing. The deposition measurements provide insight regarding the propensity of the fuel to form carbonaceous surface deposits while the headspace oxygen measurement provides information regarding the relative oxidation rate of the fuel. Surface deposition (i.e., mass accumulation on the quartz crystal) measurements are very sensitive, with the ability of monitoring changes as low as 0.1 $\mu g/cm^2$. The QCM is a batch test that is typically operated by thermally stressing 60 mL of fuel at 140°C for 15 hours. Fuel samples are air saturated prior to heating and the system is closed during operation.
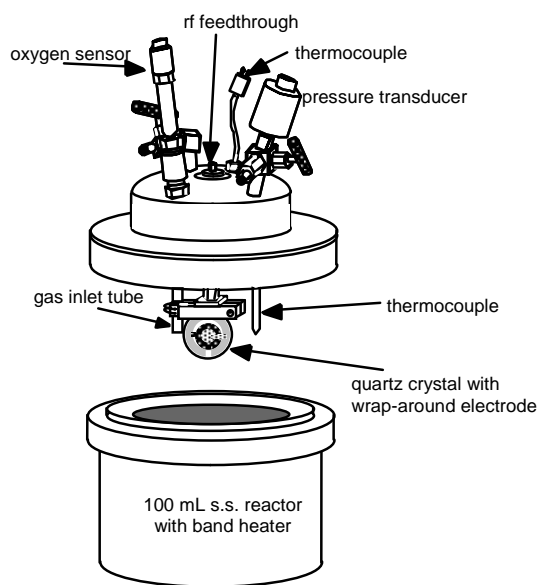
Figure 14. Diagram of the Quartz Crystal Microbalance (QCM) apparatus.

The various neat fuels and blends of 50 % FT fuel by volume with each were examined in the QCM to evaluate the relative thermal stability of these fuels. All Jet A fuels were treated with the JP-8 additive package (i.e., corrosion inhibitor/lubricity enhancer [CI/LI], static-dissipater [SDA], and fuel system icing inhibitor [FSII]) at the required specification range. The oxidation and deposition profiles from these studies are shown in Figures 15-22 while Table 15 lists the total mass accumulation values. Each figure shows the QCM profile for the neat petroleum-derived fuel, the neat FT fuel, and the corresponding 50% blend. The neat FT fuel produced significantly lower measurable deposition (0.4 $\mu g/cm^2$) than any individual jet fuels (1.0 to 3.0 $\mu g/cm^2$). The fuel blends exhibited deposition behavior between those exhibited by the neat fuels, with significant enhancement in stability for some of the blends. The reduction in deposition observed upon blending likely results from a combination of two effects: (1) dilution of the deleterious heteroatomic species in the jet fuel,[24-25, 27] and (2) reduction in the rate of oxidation of the jet fuels, lowering deposition under partial oxygen consumption conditions. It should be noted that the oxidation rate of the FT fuel (as-produced) is extremely high due to the

lack of natural antioxidants in the fuel (see discussions on Polar and Sulfur Speciation). The FT fuel had been treated with hindered phenol antioxidant to improve storage stability and prevent significant formation of hydroperoxides. During testing with the FT fuel, only a small percentage of the total oxygen was consumed, indicating that there is still unused antioxidant present in the fuel. For the fuel blends, the oxidation rate was reduced relative to the neat petroleum fuel due to the added antioxidant in the FT—this renders a reduction in the total deposition under partial oxidation conditions. Under complete oxidation conditions, the beneficial aspects from a lower oxidation rate are diminished. Figure 16 shows a fast-oxidizing fuel (F3602) and blend (F4917) which both completely consumed the available oxygen within the 15 hour test duration. Although the oxidation and deposition curves are delayed for F4917 relative to F3602, the total deposition amounts are nearly identical (2.4 and 2.3 μg/cm^2 for F3602 and F4917, respectively). Previous work has demonstrated increased deposition upon addition of hindered phenol antioxidants under complete oxygen consumption conditions, but no increase was observed for this blend. Overall, it is anticipated that blending with an FT fuel will provide improved or similar thermal oxidative stability characteristics, but should not significantly increase deposition propensity.

Table 15. QCM mass accumulation at 15 hours for eight petroleum-derived fuels, the FT fuel, and 50% by volume fuel blends.

| Sample I.D.	Sample Description	Mass Accumulation at 15 hours (μg/cm^2)
F4909	FT jet fuel	0.4
F3166	Jet A w/ JP-8 additives	1.0
F4919	50/50 blend: F3166 + F4909	0.7
F3602	Jet A w/ JP-8 additives	2.4
F4917	50/50 blend: F3602 + F4909	2.3
F3694	Jet A w/ JP-8 additives	2.0
F4921	50/50 blend: F3694 + F4909	0.9
F3804	JP-8	1.3
F4915	50/50 blend: F3804 + F4909	0.7
F4177	JP-8	2.0
F4927	50/50 blend: F4177 + F4909	0.8
F4751	JP-8	3.0
F4913	50/50 blend: F4751 + F4909	0.9
F4908	JP-8	1.7
F4923	50/50 blend: F4908 + F4909	0.5
F4911	JP-8	1.3
F4925	50/50 blend: F4911 + F4909	0.5
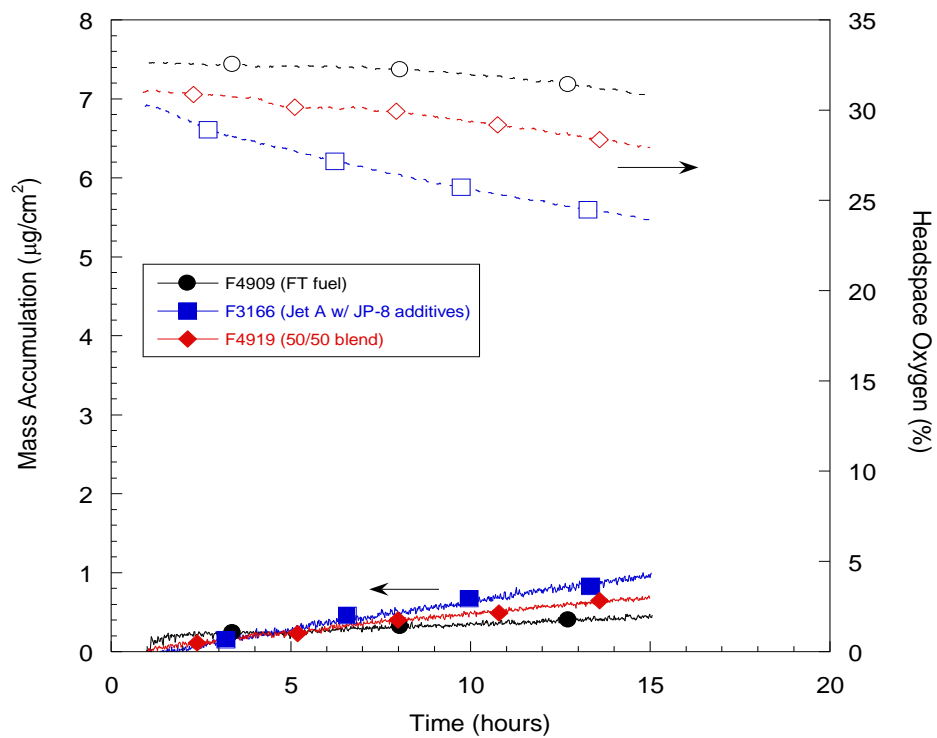
Figure 15. QCM profile of F4909, F3166 and F4919 at 140°C with air headspace.
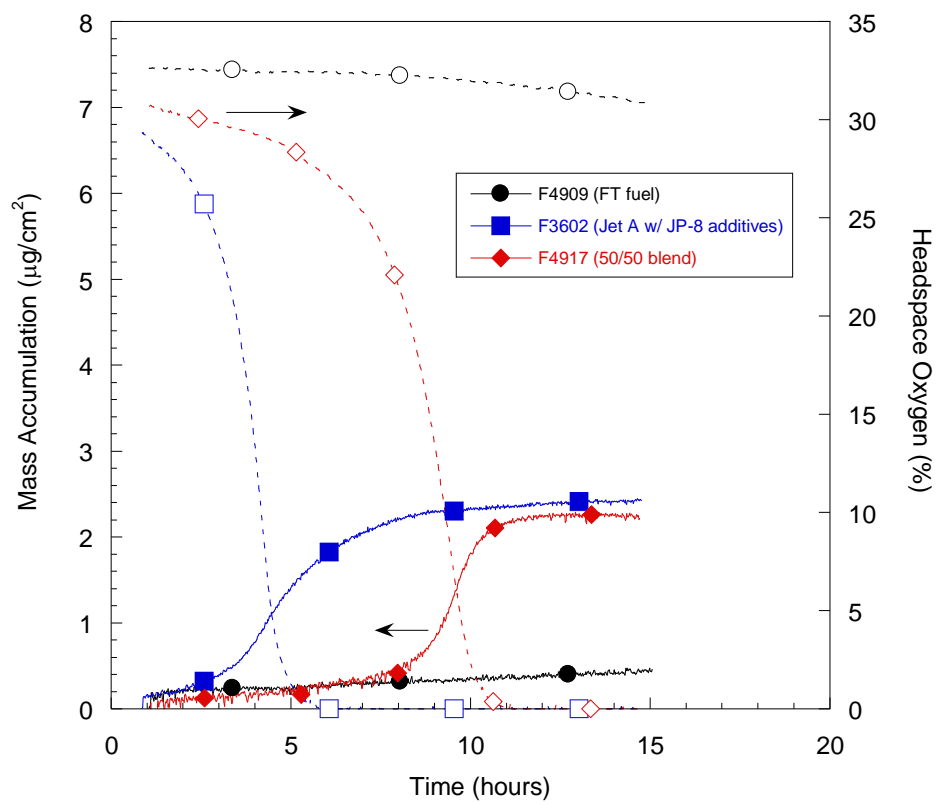

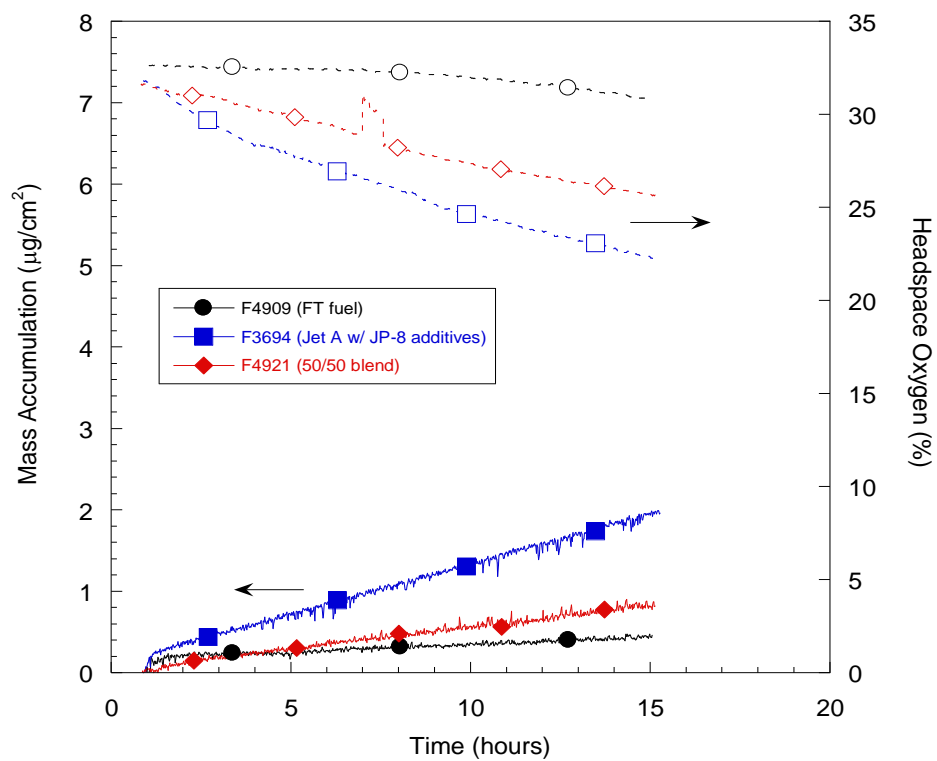**Figure 16. QCM profile of F4909, F3602, and F4917 at 140°C with air headspace.**

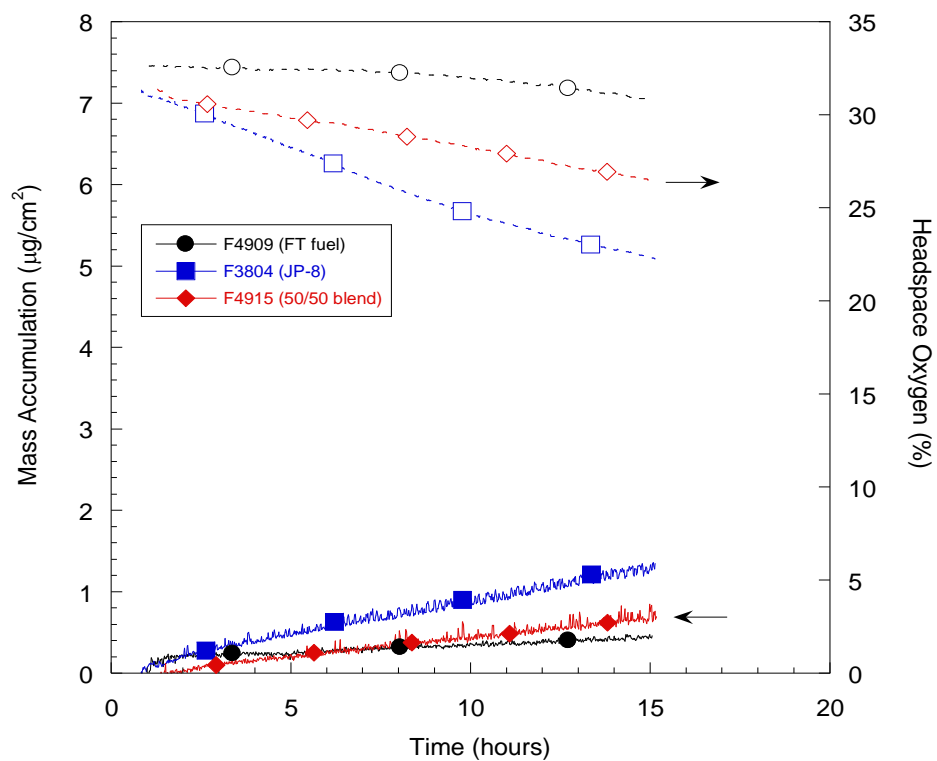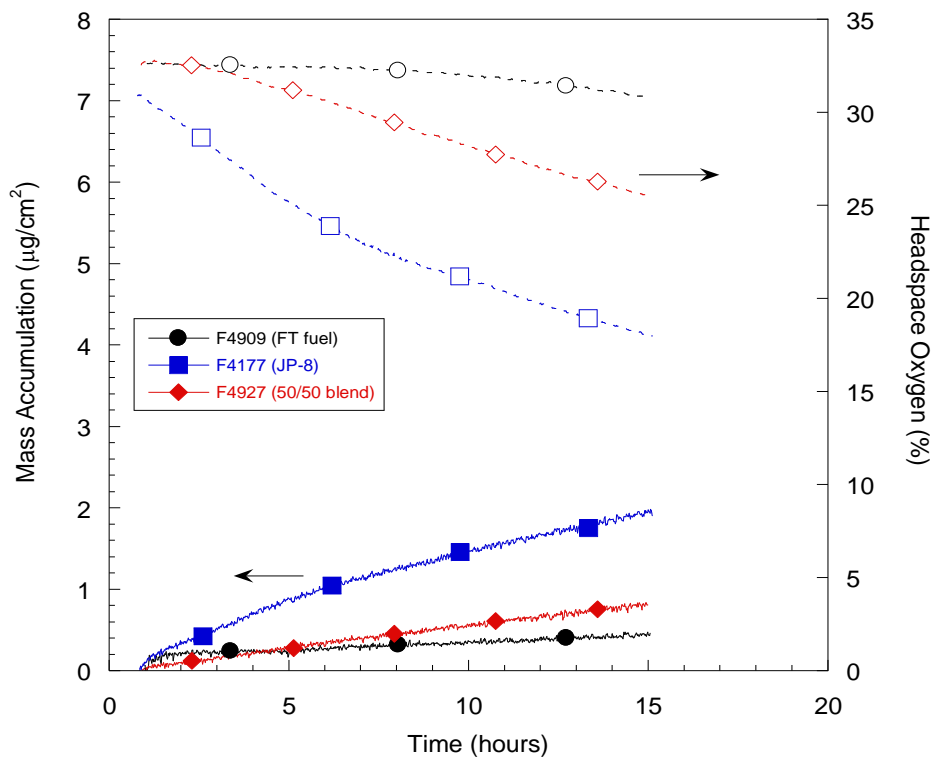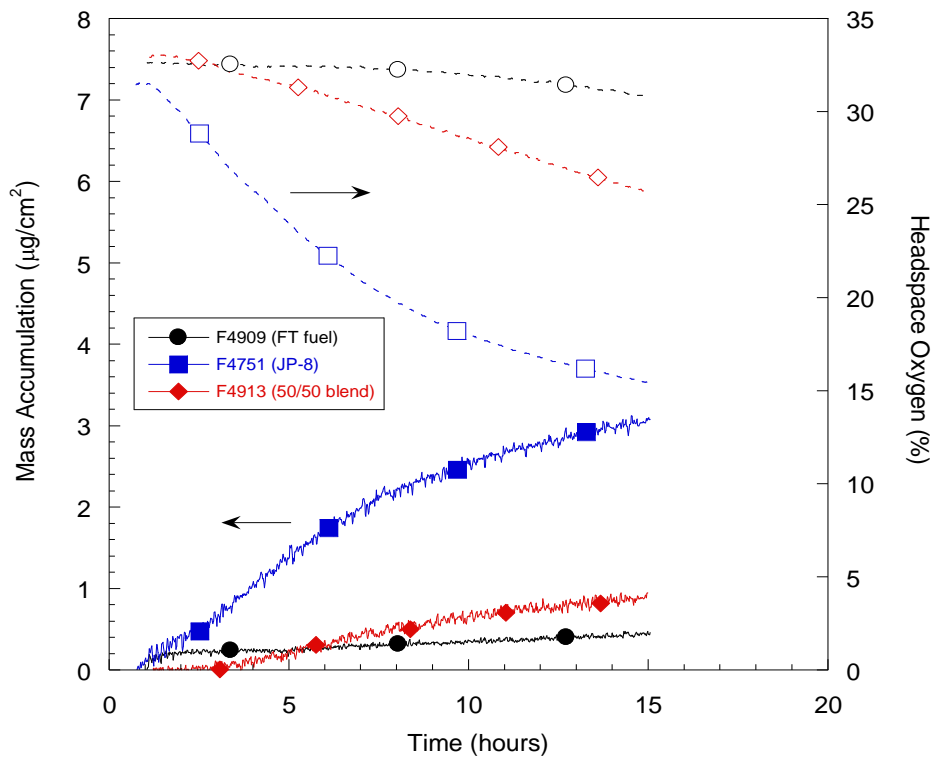**Figure 17. QCM profile of F4909, F3694, and F4921 at 140°C with air headspace.**

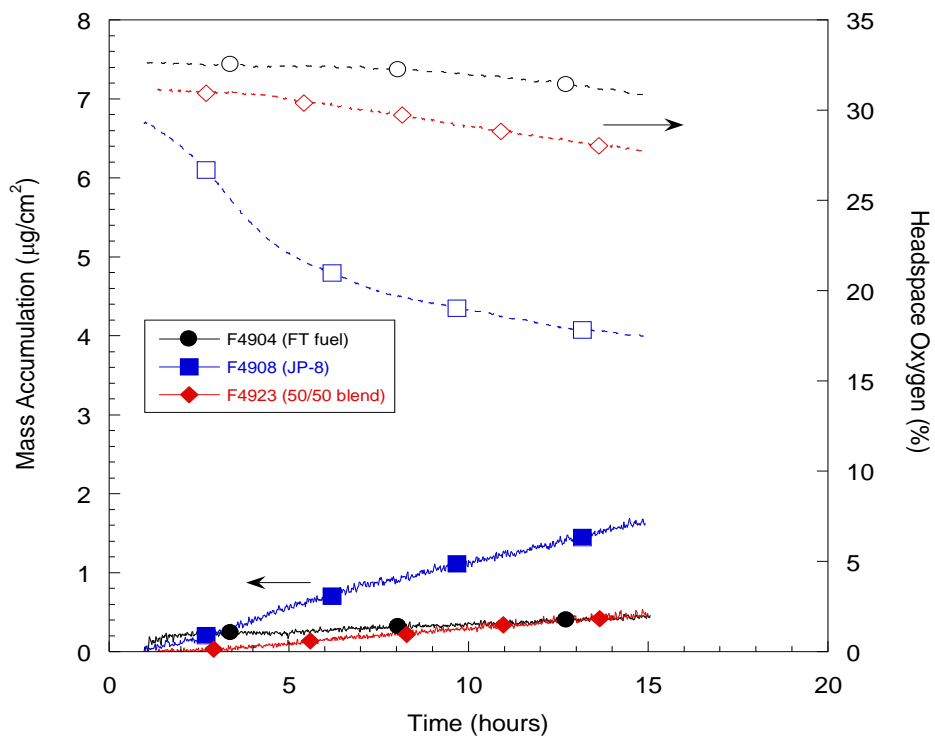**Figure 18. QCM profile of F4909, F3804, and F4915 at 140°C with air headspace.**

42

Figure 19. QCM profile of F4909, F4177, and F4927 at 140°C with air headspace.

Figure 20. QCM profile of F4909, F4751, and F4913 at 140°C with air headspace.

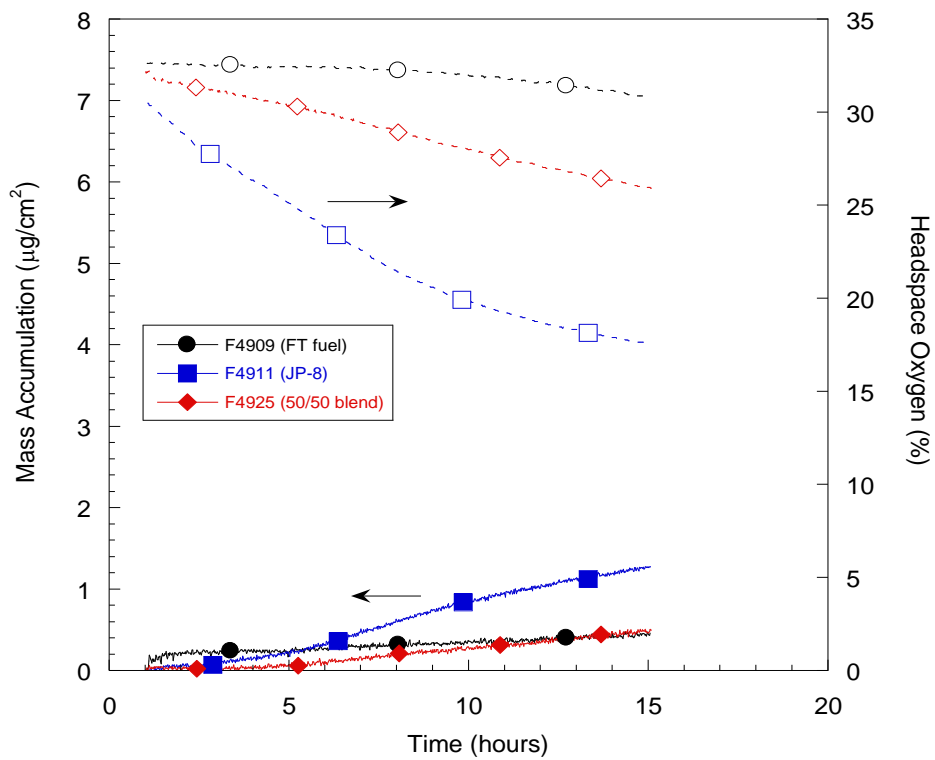**Figure 21. QCM profile of F4909, F4908, and F4923 at 140°C with air headspace.**

Figure 22. QCM profile of F4909, F4911, and F4925 at 140°C with air headspace.

3.5. Storage Stability via Low Pressure Reactor Measurements

Storage stability studies were performed to preliminarily investigate the oxidative stability of the FT fuel during storage. An important metric of fuel oxidation during storage is the extent of hydroperoxides formed. The technique employed was based on the methodology developed by the Naval Research Laboratory (NRL).[28] The studies exposed a small volume of fuel for a specific test duration at 100°C with 50 psig air overpressure. Previous NRL studies related the accelerated stress duration to ambient temperature storage via a simple Arrhenius correlation: fuel exposure at 100°C (and air/oxygen overpressure) for 24 hours approximates 9 months storage while 48 hours stress approximates 1.5 years storage. The "failure" level is based upon the previous JP-5 peroxide specification limit of 1 mequiv/kg (~800 μM, assuming fuel S.G. = 0.800) found in MIL-T-5624P. The peroxide specification limit was eliminated in 1995 update to the MIL Spec.

Studies were conducted using the FT fuel, JP-8 POSF 4911 and a 50% blend by volume for 48 hours. It should be noted that per JP-8 requirements for hydrotreated fuels, the FT fuel was treated with approved antioxidant prior to shipment to the USAF. The pre- and post-stressed fuels were analyzed for the total hydroperoxide content using a quantitative technique previously described in the literature.[29] The results of the storage stability study are shown in Figure 23. It can be observed that the hydroperoxide levels remain significantly below the "failure" limit of 800 μM. Therefore, it would be expected that the neat FT fuel or blends would have sufficient storage stability characteristics during application. However, it should be reiterated that the paraffinic FT fuel would rapidly oxidize without the addition of the artificial antioxidant due to the lack of natural antioxidants (e.g., heteroatomic species, aromatics) within the base fuel. It is necessary to insure that antioxidant is added to the synthetic fuel per the MIL-DTL-83133F specification.
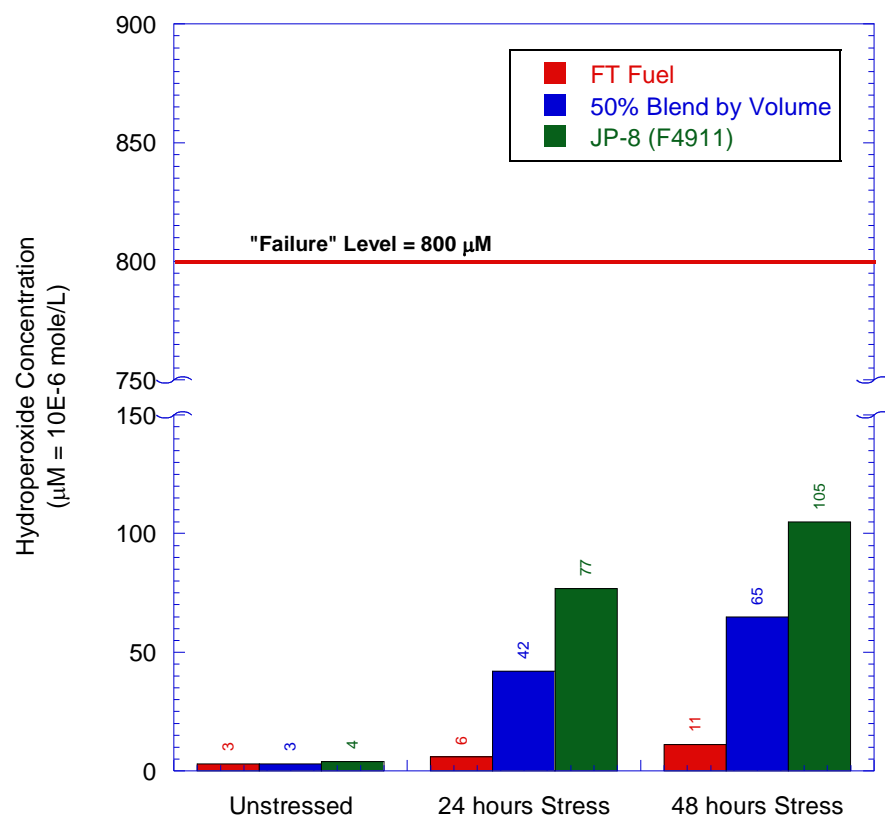
Figure 23. Measured hydroperoxide concentration from storage stability experiments conducted at 100°C with 50 psig air overpressure.
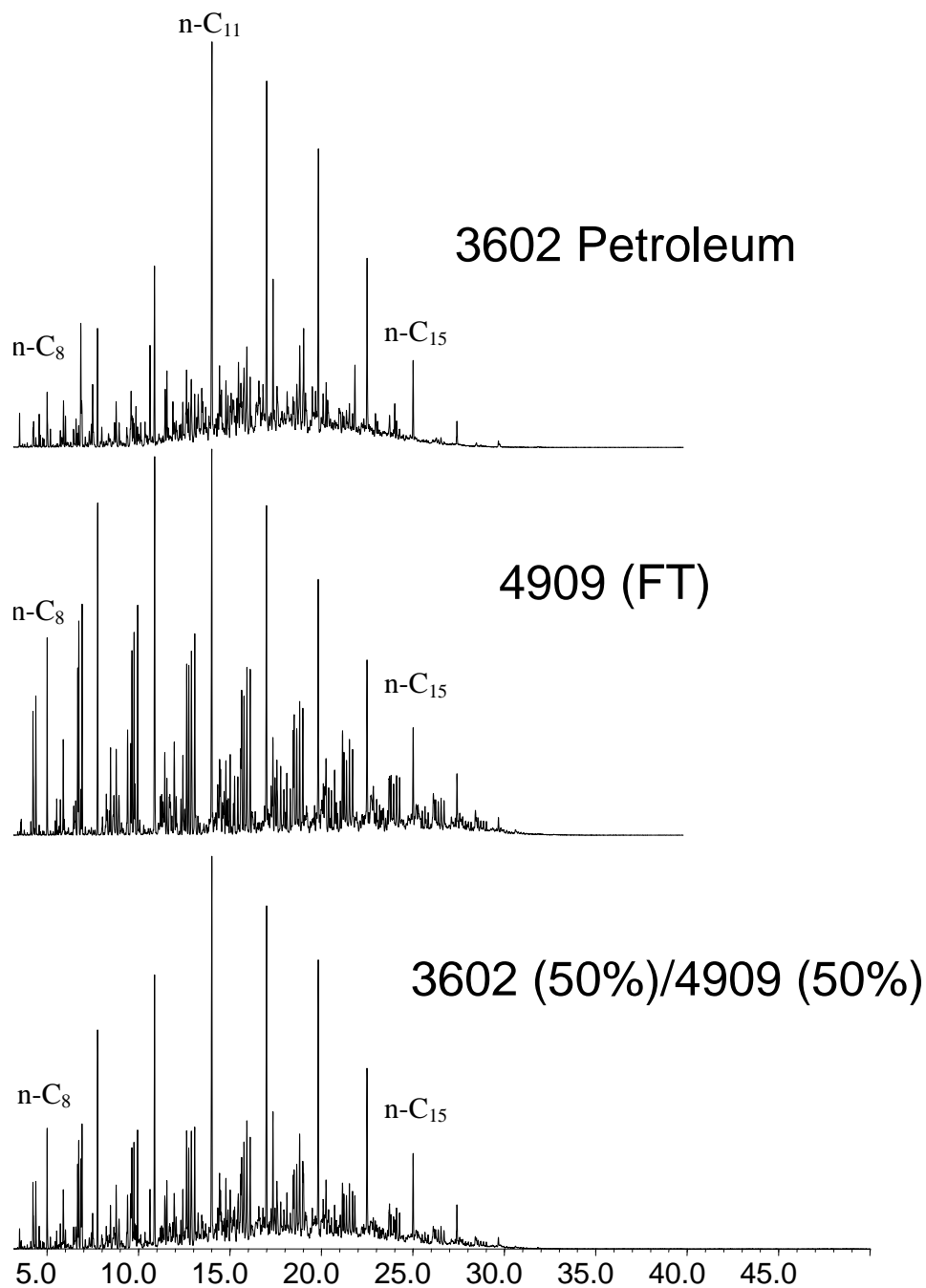
3.6. GC-MS Chromatograms of Fuels and Blends

The neat fuel samples and the 50% by volume blends were analyzed using GC-MS to investigate the relative molecular weight ranges and bulk component composition. The samples were analyzed using an Agilent 6890 GC with a 5973 Mass Selective Detector. Samples were diluted at a ratio of 20:1 with hexane and injected (split mode, 50:1) into the injector (250°C). The column used was a 30 m HP-5MS column, 0.25 mm internal diameter with 0.25 μm film thickness. The flow rate was constant (1.0 mL/min) as the column was programmed from 40°C (hold 2 minute) to 280°C at 5°C/min. The scan range for the mass spectrometer was 33-300 atomic mass units.

Results from these GC-MS analyses, shown in Figures 24-31, confirmed and highlighted the differences between the FT and petroleum-derived fuels previously discussed. The FT fuel was completely free of aromatics, which is consistent with the specification test results. The quantity of C_7 and C_8 compounds was found to be higher in the FT fuel than any of the petroleum-derived fuels; this observation is consistent with the relative flash points of the various fuels. The relative molecular weight distribution profile was shifted slightly lower for the FT fuel, which was discussed previously (*n*-alkane analysis). Despite these small differences, the FT fuel chromatogram was very similar to the petroleum samples, which is attributed primarily to the fact that the FT fuel was produced to have a similar distillation range to a typical aviation fuel. The blended samples appeared to be an average of the two chromatograms (FT and neat petroleum) in that the volatile components which were higher in the FT fuel were less pronounced.
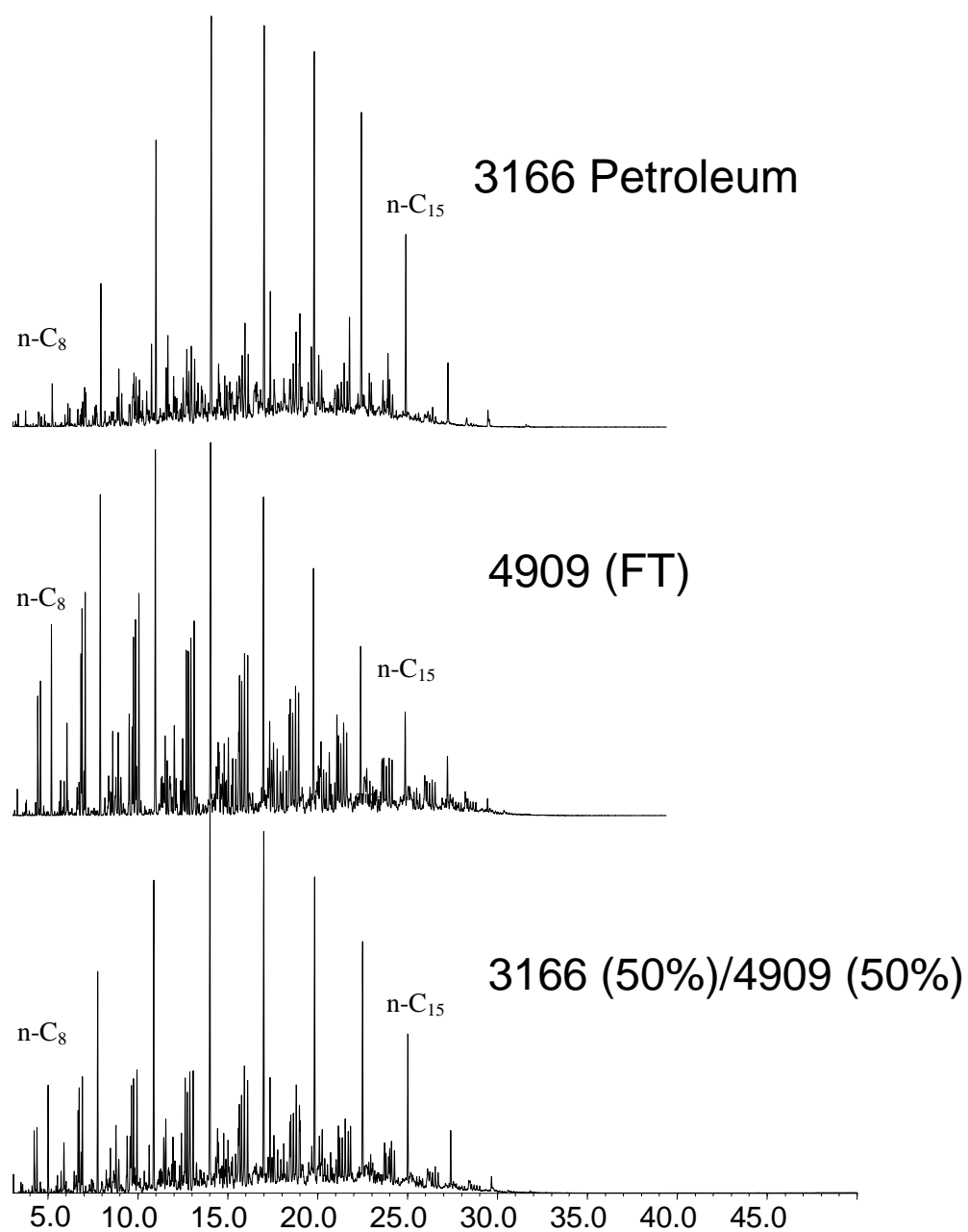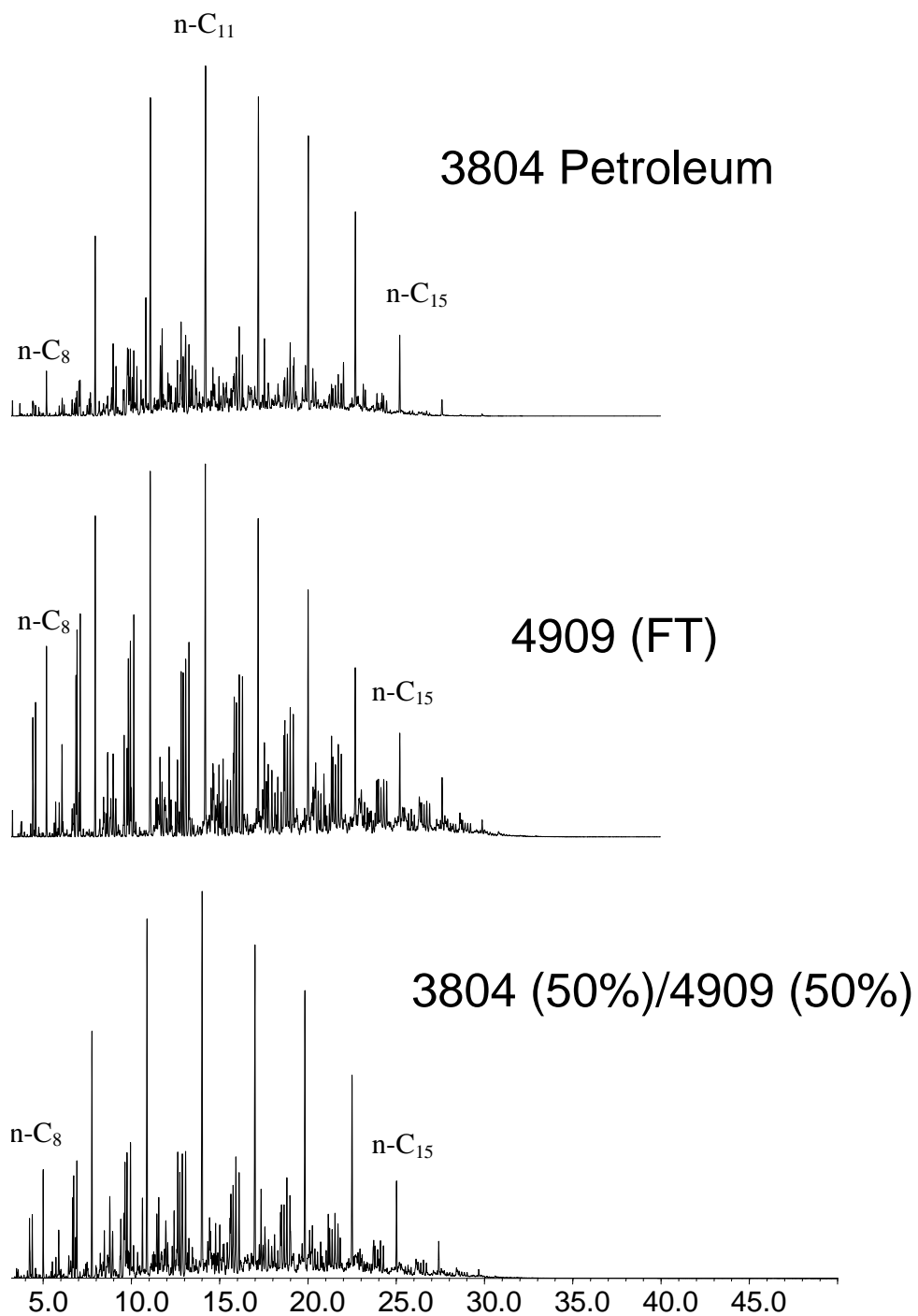
Figure 24. GC-MS chromatograms of petroleum fuel F3166 (top), FT-derived fuel F4909 (middle), and 50% blend by volume F4919 (bottom).

Figure 25. GC-MS chromatograms of petroleum fuel F3602 (top), FT-derived fuel F4909 (middle), and 50% blend by volume F4917 (bottom).
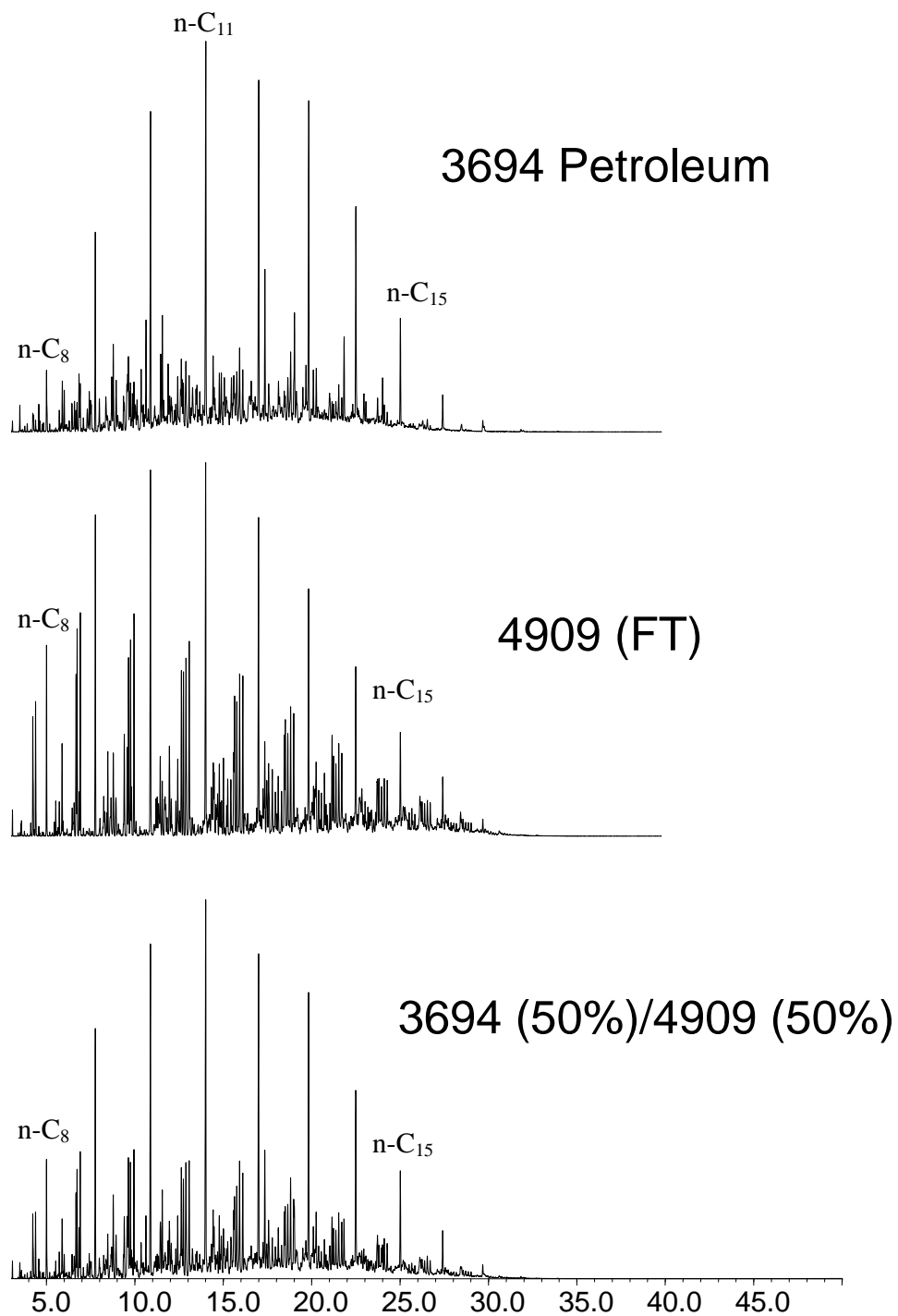
Figure 26. GC-MS chromatograms of petroleum fuel F3694 (top), FT-derived fuel F4909 (middle), and 50% blend by volume F4921 (bottom).
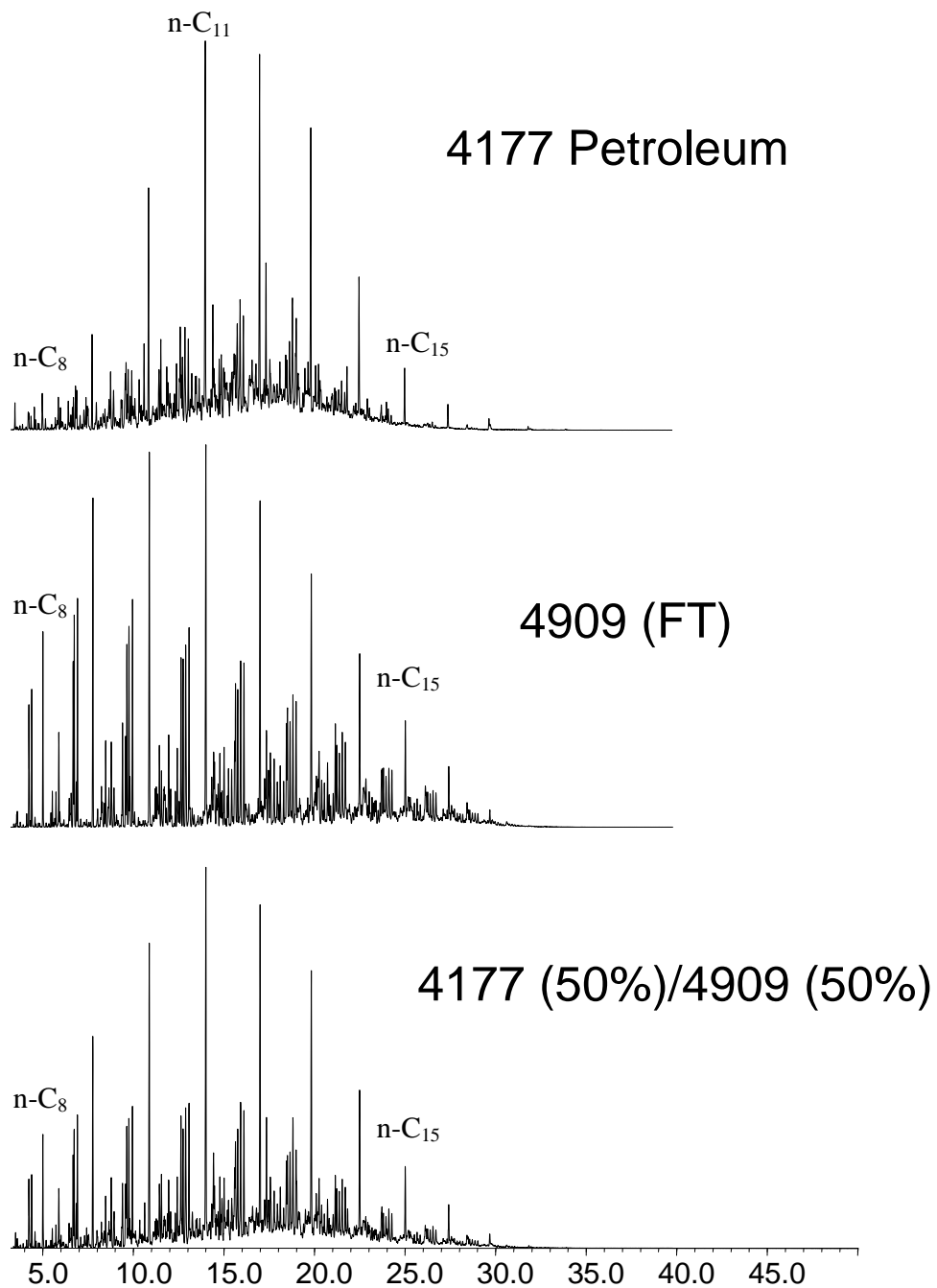
Figure 27. GC-MS chromatograms of petroleum fuel F3804 (top), FT-derived fuel F4909 (middle), and 50% blend by volume F4915 (bottom).

Figure 28. GC-MS chromatograms of petroleum fuel F4177 (top), FT-derived fuel F4909 (middle), and 50% blend by volume F4927 (bottom).

n-C$_{11}$

4751Petroleum

n-C$_{15}$

n-C$_8$

n-C$_8$

4909 (FT)

n-C$_{15}$

4751(50%)/4909 (50%)

n-C$_8$

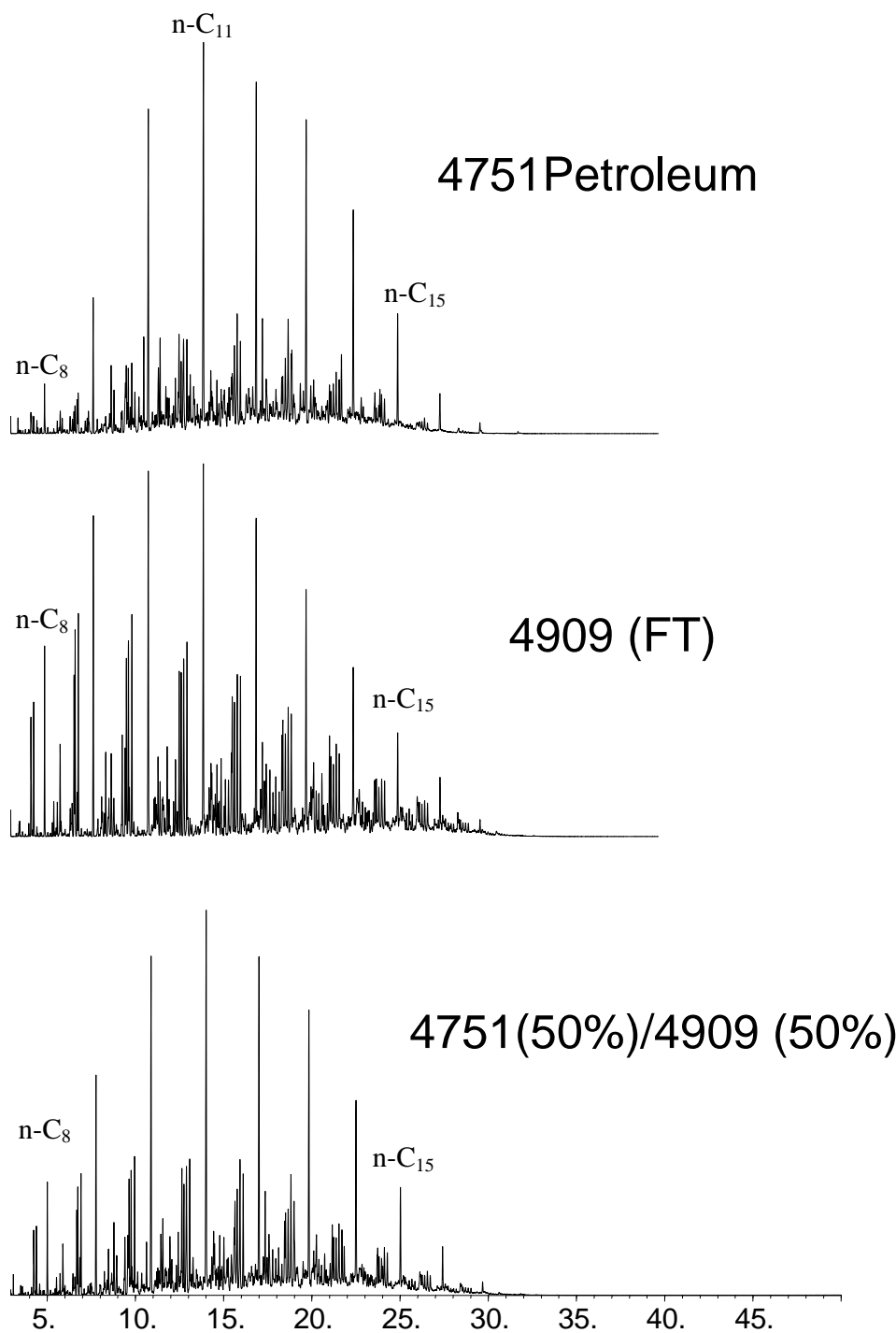n-C$_{15}$

5. 10. 15. 20. 25. 30. 35. 40. 45.

Figure 29. GC-MS chromatograms of petroleum fuel F4751 (top), FT-derived fuel F4909 (middle), and 50% blend by volume F4913 (bottom).

Figure 30. GC-MS chromatograms of petroleum fuel F4908 (top), FT-derived fuel F4909 (middle), and 50% blend by volume F4923 (bottom).
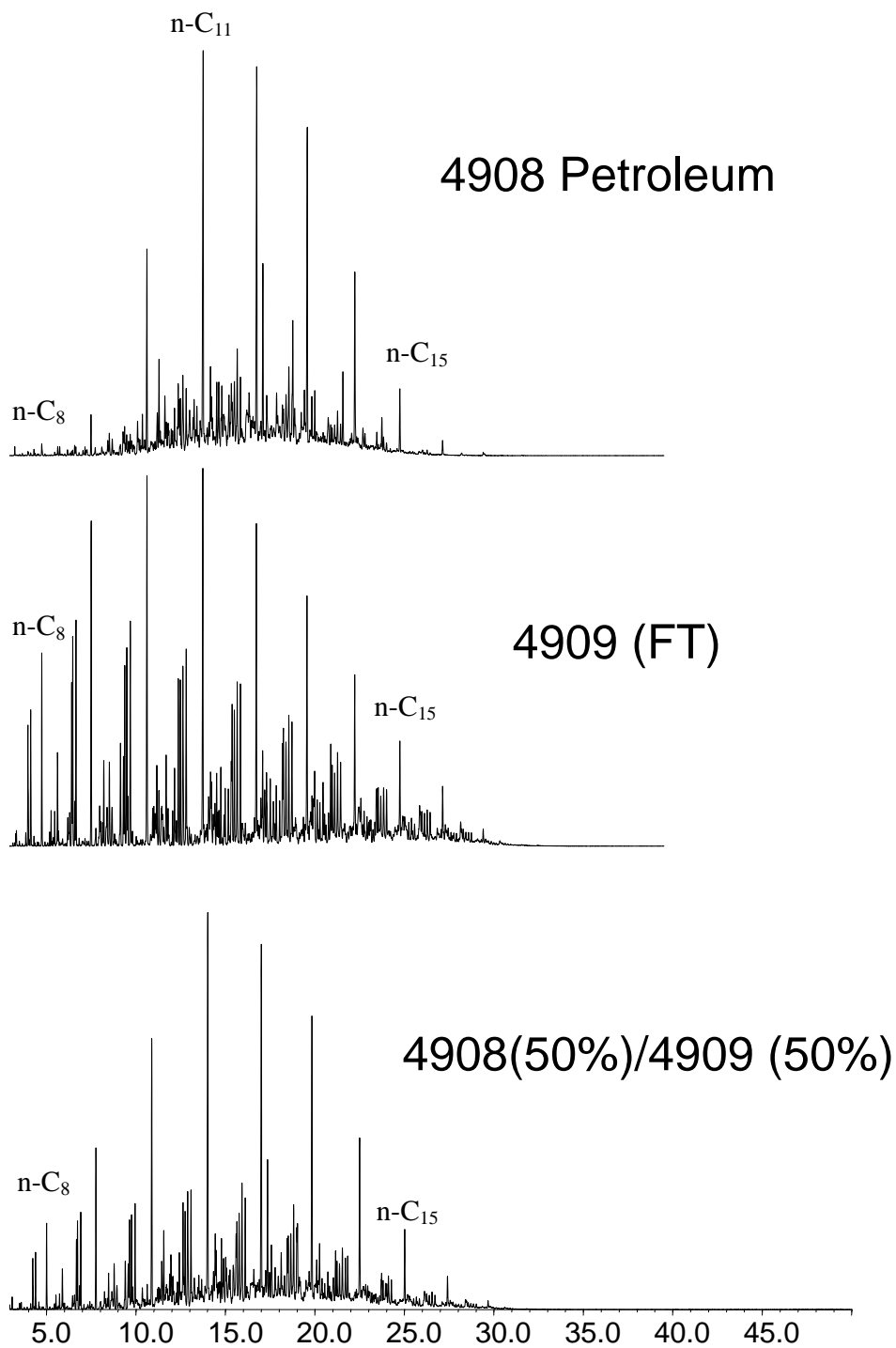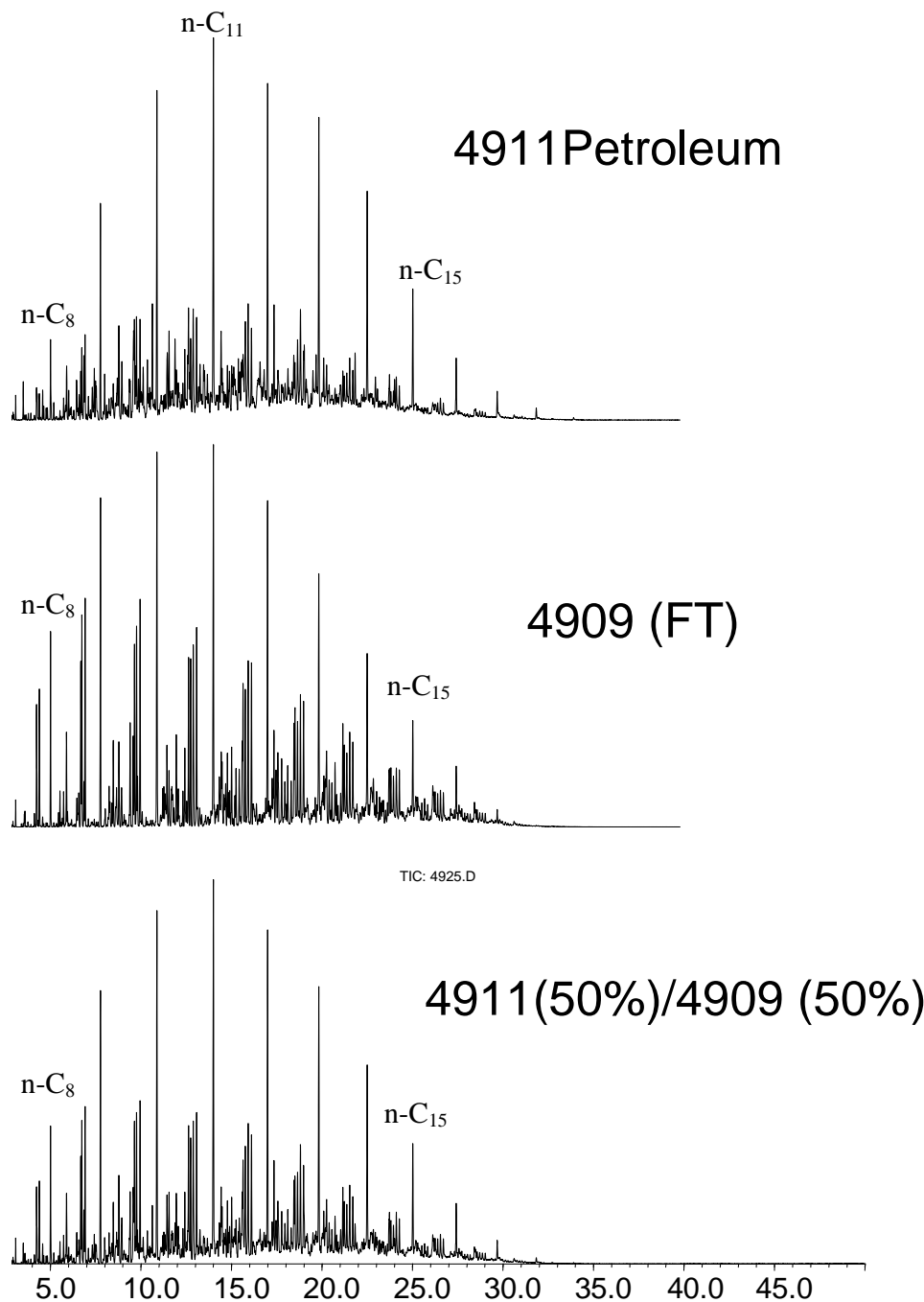
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Figure 31. GC-MS chromatograms of petroleum fuel F4911 (top), FT-derived fuel, F4909 (middle), and 50% blend by volume F4925 (bottom).

4. Conclusions and Future Work

Blending of an FT-derived *Iso*-Paraffinic Kerosene (IPK) which had a similar distillation range to a typical jet fuel and high *iso*-/normal alkane ratio with several petroleum-derived fuels showed a linear dependence in the specification and non-specification properties with blend ratio. Determination and understanding of this dependence is important because it allows for the prediction of anticipated fuel properties during blending. This predictability will allow blends to be produced which will have known levels of important properties, such as density, aromatic content, hydrogen content, and heat of combustion. In addition, other properties of fuel blends (sulfur content, emissions, overall quality) can be improved by the addition of FT. It should be noted that these linear results are most likely due to the inherent nature and volatility range for the IPK used. Further investigation of non-specification and "Fit-for-Purpose" properties is required to assist in ultimate implementation and determine any limitations which exist. Understanding of the property dependence with blending will allow for statistical analysis using historical fuel property distribution data to be performed to investigate expected fuel properties and variability as a function of blend ratio.

5. Acknowledgements

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7. Appendix – Dynamic Viscosity Curves

Scanning Brookfield Viscosity

Scanning Brookfield Viscosity

Scanning Brookfield Viscosity

- FT F4909 (FP: - 51C)
- 3694 w/ JP-8 Additives (FP: - 50C)
- 4920 (25% 4909/ 75% 3694) (FP: - 51C)
- 4921 (50% 4909/ 50% 3694) (FP: - 52C)

Scanning Brookfield Viscosity

- FT F4909 (FP: - 51C)
- JP-8 F3804 (FP: - 49C)
- F4914 (25% F4909/ 75% F3804) (FP: - 50C)
- F4915 (50% F4909/ 50% F3804) (FP: - 53C)

Scanning Brookfield Viscosity

Scanning Brookfield Viscosity

63

Scanning Brookfield Viscosity

Legend:
- FT F4909 (FP: - 51C)
- JP-8 F4908 (FP: - 51C)
- F4922 (25% F4909/ 75% F4908) (FP: - 52C)
- F4923 (50% F4909/ 50% F4908) (FP: - 54C)

Scanning Brookfield Viscosity

Legend:
- FT F4909 (FP: - 51C)
- JP-8 F4911 (FP: - 52C)
- F4924 (25% F4909/ 75% F4911) (FP: - 51C)
- F4925 (50% F4909/ 50% F4911) (FP: - 52C)